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An open multi-physics framework for modelling wildland-urban interface fire evacuations

Enrico Ronchi[a,*], Steven M.V. Gwynne[b,f], Guillermo Rein[c], Paolo Intini[a,d], Rahul Wadhwani[c,e]

[a] Department of Fire Safety Engineering, Lund University, SE-22100 Lund, Sweden
[b] National Research Council Canada, K1A 0R6 Ottawa, Canada
[c] Department of Mechanical Engineering, Imperial College London, SW7 2AZ London, UK
[d] Department of Civil, Environmental, Land, Building Engineering and Chemistry, Polytechnic University of Bari, 70125 Bari, Italy
[e] Centre for Environmental Safety and Risk Engineering, Victoria University, Melbourne, VIC 3030, Australia
[f] Movement Strategies, 31-35 Kirby Street, London EC1N 8TE, UK

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ABSTRACT

Fire evacuations at wildland-urban interfaces (WUI) pose a serious challenge to the emergency services, and are a global issue affecting thousands of communities around the world. This paper presents a multi-physics framework for the simulation of evacuation in WUI wildfire incidents, including three main modelling layers: wildfire, pedestrians, and traffic. Currently, these layers have been mostly modelled in isolation and there is no comprehensive model which accounts for their integration. The key features needed for system integration are identified, namely: consistent level of refinement of each layer (i.e. spatial and temporal scales) and their application (e.g. evacuation planning or emergency response), and complete data exchange. Timelines of WUI fire events are analysed using an approach similar to building fire engineering (available vs. required safe egress times for WUI fires, i.e. WASET/WRSET). The proposed framework allows for a paradigm shift from current wildfire risk assessment and mapping tools towards dynamic fire vulnerability mapping. This is the assessment of spatial and temporal vulnerabilities based on the wildfire threat evolution along with variables related to the infrastructure, population and network characteristics. This framework allows for the integration of the three main modelling layers affecting WUI fire evacuation and aims at improving the safety of WUI communities by minimising the consequences of wildfire evacuations.

1. Introduction

Fires at wildland-urban interface (WUI) pose a significant challenge to the residential population, in terms of required mitigation efforts on the existing infrastructure. In fact, on top of the worldwide ecological impacts and economic losses associated with wildfires, there is also the problem of threats to the communities living in the WUI. These communities often have to evacuate to save their lives (Caton et al., 2016). Despite the common knowledge that wildfire evacuations are frequent worldwide, there is no global data available – only partial data-sets and associated analysis exist. As an example, between 1980 and 2007, there were 547 evacuations involving a total of over 200,000 people due to wildfire events in Canada alone (Beverly and Bothwell, 2011). Approximately 90,000 people were evacuated during the 2016 Fort McMurray disaster event alone (Westhaver, 2017). WUI fire disasters can involve many structures in a short period of time, overwhelming protection and mitigation measures; for instance, the Oakland fire in 1991 in California (Pagni, 1993), the Black Saturday fire in 2009 at Kilmore East in Victoria, Australia (Cruz et al., 2012), and the Fort McMurray fire in Alberta, Canada in 2016 (Westhaver, 2017), all quickly moved from vegetation to multi-structure incidents.

In addition, the need for large-scale evacuation is increasing as more people live in areas at high risk of wildfires. Housing developments in WUI areas are particularly appealing to people given their low cost, access to recreational pursuits, and the aesthetic benefits of being closer to nature (Wolshon and Marchive, 2007) as demonstrated by the number of houses built in WUI region, which in the US alone has increased by ~50% from 1990 to 2010 (Radeloff et al., 2018). Therefore, WUI incidents affect more people and become more severe (as they would affect more households). The situation is likely to evolve in countries which have a history of severe wildfires events such as the US, Canada, Australia and Southern Europe. Similarly, other regions which are susceptible to wildfires (e.g. South America, Africa, Northern Europe) may be increasingly vulnerable due to climate change (Jolly

* Corresponding author.
E-mail address: enrico.ronchi@brand.lth.se (E. Ronchi).

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Table 1
Recent major North American Wildfires in past 30 years.[a]

Incident	Date	Loss	Direct impact on local population
Fort McMurray, Canada	2016	US$ 7 billion	3600+ buildings 2 fatalities 88,000 evacuees
Oakland Hills Fire, CA	1991	US$ 2.5 billion	25 fatalities/150 injuries 3000+ buildings
South California Firestorm, 30 fires	2007	US$2.0 billion	7 fatalities 2000+ buildings 500 k evacuees 210,000 ha
Cerro Grande Wildland Fire, Los Alamos	2000	US$1.3 billion	420 homes 100 buildings
Wildland fire Cedar, Julian, CA	2003	US$1.3 billion	2750+ buildings 15 fatalities
"Old" Wildland Fire, San Bernadino, CA	2003	US$1.2 billion	993 homes 6 deaths
British Columbia Wildfires	2003	US$0.5 billion	334 homes 3 fatalities 255,000 ha 36,000 evacuees
Southern California Wildfires	2008	US$0.9 billion	4000+ fires 13 fatalities
Laguna Beach Wildland Fire, CA	1993	US$0.5 billion	400+ homes
Slave Lake	2006	US$ 0.6 billion	700+ homes/1 fatality 4700 ha 15,000 evacuees
Richardson Fire	2011	US$0.4 billion	Affected oil sands refinery of 3000 employees 700,000 ha

[a] https://inciweb.nwcg.gov/ and https://www.nifc.gov/fireInfo/fireInfo_stats_histSigFires.html.

et al., 2015). For instance, the eight worst years for US wildfires occurred in the last 15 years (Paveglio et al., 2015). This can be attributed to (a) increased fire activity, (b) hotter/drier summers, (c) stronger winds, (d) insect infestations, and (e) residential population growth near/in the wilderness (Paveglio et al., 2015).

The social and physical characteristics of WUI communities present a special challenge that needs to be addressed when ensuring life safety. Social factors like culture, age and income can have a direct impact on the evacuation response (for example, due to the availability of a vehicle for evacuation) (Cohn et al., 2006; Folk et al., 2019; McCaffrey et al., 2018; McLennan et al., 2018; Vaiciulyte et al., 2018). Varying density levels of households, the layout and possibly reduced capacity of the road network, and the surrounding geography affecting firefighting interventions contribute to the capacity of the community to reach a place of safety in response to a wildfire incident (Cova, 2005).

Past incidents (see Table 1 for a list of major North American wildfires) like the 2016 Fort McMurray fire, Canada (Westhaver, 2017) show how important the availability of predictions of future conditions that inform decision making might be. During the 2016 Fort McMurray fire in Canada, multiple evacuations were triggered by the wildfire (Westhaver, 2017). During the course of the event, areas which were considered safe due to temporary favourable wind conditions had to later be evacuated at a later stage due to the evolution of the wildfire (with some populations being evacuated several times) (KPMG, 2016). An increased situational awareness (Seppänen and Virrantaus, 2015) could have been a significant help to reduce the consequences of the wildfire; i.e. to prevent multiple evacuations in the former case and increase the margin between evacuation and wildfire arrival in the latter case.

In this context, a simulation framework that can establish evacuation performance ahead of time (at different temporal scales, i.e. from minutes to hours, days and years) would be a game changer. Nevertheless, to date, such type of comprehensive tools able to inform, train or aid the evacuation response and the decision making in case of wildfire does not exist. Previous attempts to develop simulation frameworks for wildfire evacuation scenarios generally model the various domains and levels at different levels of sophistication and granularity – affecting the consistency across the modelling platform (Beloglazov et al., 2016; Dennison et al., 2007).

To develop a novel integrated framework, the first step consisted in the identification of the three key layers which affects WUI evacuation performance: wildfire propagation, pedestrian response, and vehicular transport (i.e., traffic). The term layer here refers to the type of modelling domain represented, while the term model is used to refer to the tool adopted for the representation of such layer. The proposed system should therefore be based on the multidisciplinary premise that these models can communicate with each other to provide quantitative and qualitative feedback before and during an incident.

The present paper focuses on detailing the system specification of an open multi-physics modelling framework to aid decision making in WUI fire evacuation scenarios. This is based on a published report of the project associated with this work (Ronchi et al., 2017). During the project, a technical panel, including subject matter experts and end users, had an advisory role on the research activities in order to provide feedback on the current needs in terms of operational models for emergency management (both in real time and in the planning stage). The end goal of this effort is to develop a computer model which is freely available for disaster management. The system specification was developed to shape the required model functionality, performance, data exchange, input requirements, and output capabilities in relation to required spatial and temporal scale. To develop this framework, a variety of modelling tools capable of representing wildfire behaviour, pedestrian movement, and traffic evacuation were examined to determine which attributes of each model might be employed in relation to the WUI scenarios under consideration.

2. Methodology

Timelines and factors that influence the incident outcome were identified (also through the analysis of case studies) to examine key phases of WUI incidents, inform expected model content and the subpopulations active in the incident as well as to identify model functionality, potential end-users and application types. This was later used to develop general timelines derived from those employed in fire engineering for building design (the so-called ASET/RSET timeline – available and required safe egress time). This required the development of an engineering time-line for WUI incidents that might be expressed in the form of a simplified equation (see Eq. (1) for an example referring to an evacuation using vehicles). This is a simplification which only refers to a single location and assumes that should an incident reappear in the same location (e.g. reignite, be subject to firebrands, etc.), a new timeline is employed.

$$WASET > WRSET = t_T = t_d + t_{FDA} + t_{FDI} + t_N + t_{prep} + t_{foot} + t_{veh} + t_{ref} \tag{1}$$

where t_T is the time for the population to reach safety (named also WRSET, Wildland-urban interface required safe egress time), t_d is the time for the incident to be detected after ignition, t_{FDA} is the time spent by the fire department assessing the situation on site, t_{FDI} is the time spent by the fire department intervening and attempting to control the incident, t_N is the time for the population to be notified once intervention has been deemed unsuccessful, t_{prep} is the time for a resident to complete preparations after they have initially been notified, t_{foot} is the time for the population to move on foot (e.g. walk to a place of safety or to a vehicle), t_{veh} is the time for the population to move into a vehicle, and finally t_{ref} is the time for the individual to be on-boarded at a place of safety (see Fig. 1 for an example of WRSET timeline). It should be noted that the elements of the timeline could possibly be placed in different orders, i.e. the sequence of the events might differ.

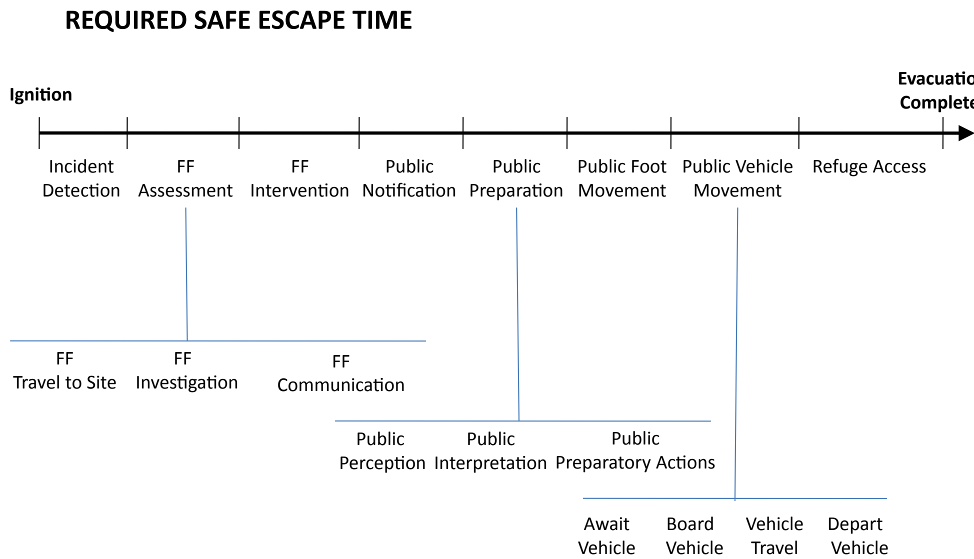

Fig. 1. Example of WRSET (WUI RSET) timeline (Note: FF refers to firefighters).

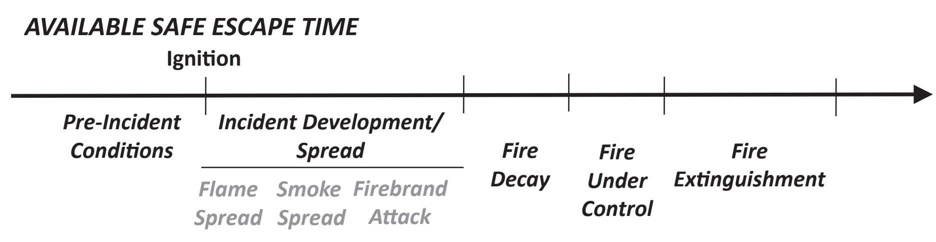

Fig. 2. WASET (WUI ASET) timeline.

Similarly, a *WASET* has been developed to represent the wildland-urban interface available safe egress time (Ronchi et al., 2017). This timeline considers the pre-incident conditions, the incident development/spread (starting with ignition and made of flame spread, smoke spread and firebrand attack), fire decay, fire under control and finally fire extinguishment (see Fig. 2). It should be noted that this timeline only refers to a single location and assumes that should an incident reappear (e.g. reignite, be subject to firebrands, etc.), a new timeline would effectively need to be employed. WASET should always be greater than WRSET (including a certain margin of safety) to ensure safety conditions (see Eq. (1)).

After a preliminary review of case studies, development of a WRSET/WASET timelines and study of existing tools, the analysis of the three main modelling layers of WUI fire evacuation scenarios was performed for each of the three specific subject domains (Gwynne et al., 1999; Kuligowski et al., 2010; Pel et al., 2012; Sullivan, 2009b, 2009c, 2009a), this being expanded to evaluate the specific requirements of WUI fire scenarios.

Several existing technologies were also examined that make use of predicted data including risk assessment tools, online mapping systems and existing integrated systems. These were reviewed to better understand potential technological end users of the proposed system. Currently available models for each of the three domains were then examined.

A systematic approach for reviewing the model characteristics was employed (see Fig. 3). This included the development of a common review template that was later modified to fit different modelling layers. Key variables and layers which are present in the three components were identified and assessed. This included the analysis of the most common modelling approaches, variables and sub-models used to produce output required for the integration and the associated needed inputs. The characteristics of an ideal model for WUI fire evacuation were then identified and existing models were evaluated in relation to a set of previously identified criteria.

The model reviews were conducted to examine the current functionality and model assumptions and to develop a set of questions to determine required model functionality and performance within an integrated simulation system.

3. Model review and framework requirements

The assessment of the requirements of the WUI fire evacuation framework is conducted starting from a three-step analysis, namely 1) assessment of the WUI spatial and temporal scales considered in existing modelling layers, 2) definition of the required and plausible level of model refinement in relation to the WUI scales, and 3) analysis of the required capabilities of modelling tools in light of existing models for the three layers under consideration.

3.1. Assessment of WUI scales

The first step for the assessment of the requirements of an integrated system for WUI incidents is the definition and classification of the spatial scales. The definition of the spatial domains is quite a complex issue in WUI incidents given the presence of the spotting phenomena (Leonard and Blanchi, 2005; Wang, 2006) which might lead to the appearance of fire fronts far away from the starting location of the wildfire. The combination of several variables also affects the spatial boundaries of the wildfire itself and the population involved in the evacuation (e.g. topography, household density, road network configuration). Different categories of spatial scale have therefore been suggested when referring to different modelling domains. The terminology has been grouped into different classes in relation to the spatial scale under consideration. Table 2 presents the classes adopted (the classes

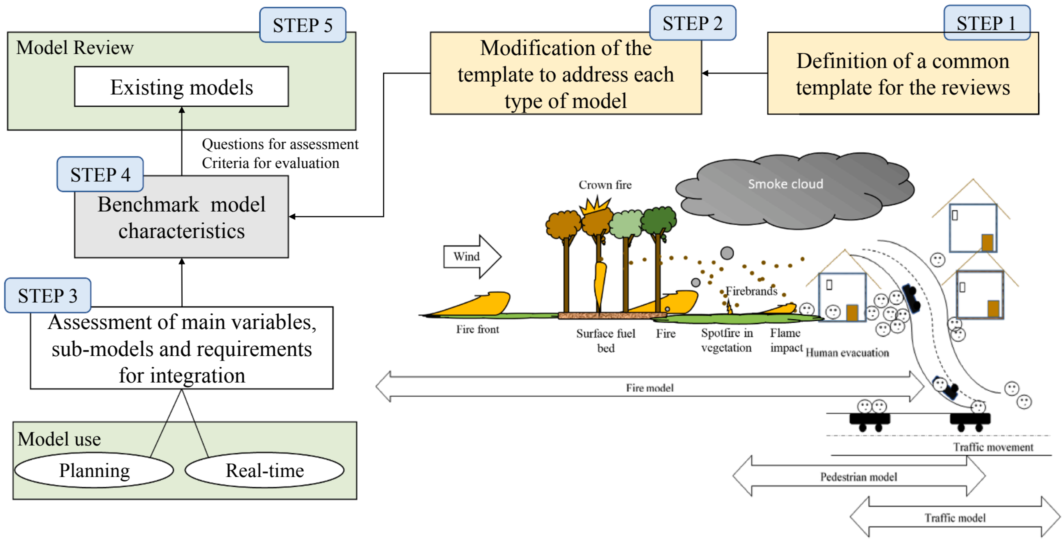

Fig. 3. Systematic approach employed for the assessment of the three modelling layers (wildfire, pedestrian and traffic models).

Table 2
Classes of spatial scales in different modelling domains.

Spatial class	Modelling domain		
	Fire	Pedestrian	Traffic
1	Tree	Individual	Individual
2	Plot	Room	Corridor
3	Forest	Structure	Regional
4	Region	Multi-structure	State
5	Multi-region	Community	Multi-state

start from 1 that is the smallest spatial scale to 5 that is the largest).

It should be noted that the spatial scale of a WUI incident in an integrated modelling framework should consider the combination of the scales of different domains, i.e. there might be scenarios in which different classes apply for different modelling domains. For instance, a very large wildfire at multi-state level [spatial class 5] with a limited number of households may involve a lower number of entities in the pedestrian (e.g., multi-structure, [spatial class 4]) and traffic domain (e.g., traffic is triggered only at a regional level [spatial class 3]). This classification allows the consideration not only of the area involved by the wildfire itself but also population/household density as a variable.

Besides the spatial scale, the evacuation process heavily relies on the prediction of the propagation of the hazard over time; i.e. the duration and dynamics of the event. This issue also presents several complex variables, since the evolution of wildfire might involve the re-start of fire fronts at different points in time at locations where the threat had previously been considered temporarily over.

3.2. Level of model refinement

The criticality of model refinement on the results produced can be derived from differences between the data collected and the aggregation level under consideration (Trainor et al., 2012). It is therefore of particular importance for a modeller to assess the selection of a certain level of refinement for modelling given the data available (Trainor et al., 2012); i.e., whether it is constraining performance without benefitting the outcome. Three levels of model refinement are suggested: simplified, hybrid and refined (Wolshon and Marchive, 2007). The present work employs this three-point scale of model refinement. Different categories apply for each of the models under consideration given the different subject domains addressed:

(a) Simplified models can refer to an empirical modelling approach for wildfire spread, flow-based for pedestrian modelling, macroscopic for traffic modelling
(b) Refined models can refer to a physics-based approach for wildfire spread, agent-based for pedestrian modelling, microscopic for traffic modelling
(c) Hybrid models refer to a combination of the different level of refinement for all models (e.g., a mesoscopic approach for traffic models) – either by employed a moderately granular approach throughout or adopted a varied degree of refinement for different aspects of the modelling process.

Figs. 4–6 provide information on the achievable level of refinement in relation to the temporal scale of the event (i.e., the time within which the simulated results need to be delivered) and the spatial scale (i.e., the elements that should be simulated) – for each of the three model domains. The temporal scale can also be divided in relation to the application type (i.e. real-time application vs. a planning application). The categories used were determined by the background analysis conducted and the model reviews themselves. It should be noted that this involves a degree of subjective assessment and is therefore only indicative; nevertheless, it needed to be performed to identify how constraints propagate throughout the system. The same approach is adopted in each case – only the terminology employed on the x-axis differs to reflect the classes used in each domain. In each graph a polygon is included to represent the application types for each of the modelling refinement. These polygons overlap in a number of areas, indicating that more than one modelling approach might be applied for certain scenarios. The terms employed in each figure reflect those employed in each modelling domain.

Figs. 4–6 shows that models refinement affects the ability to represent certain scenarios – irrespective of the time available. This is because models may not able to simulate the spatial entities given their level of modelling resolution. For instance, a simplified pedestrian model based on flow calculations is not able to represent the movement or decision-making of individual evacuees (see Fig. 5). More refined models allow scenarios to be simulated with increased refinement, but they are not generally usable for real-time application given the requirement of a high computational time, especially involving larger spaces.

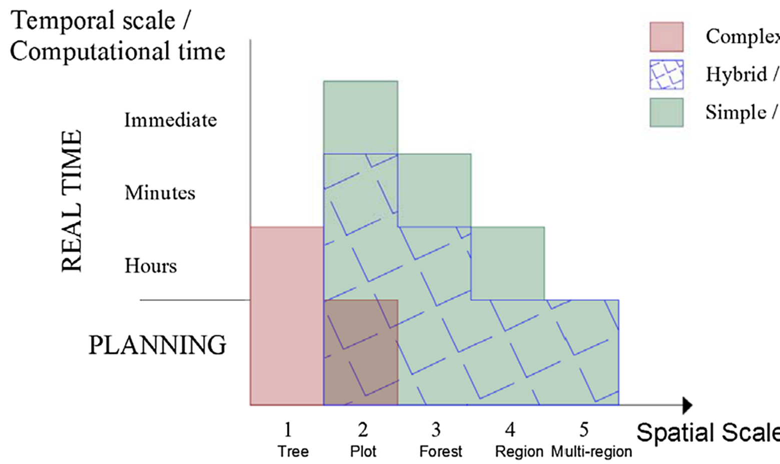

Fig. 4. Suggested model application scales given model refinement for wildfire models. The spatial scale for the wildfire models is divided into five categories and they are related to the temporal scale of the event (for both real-time and planning applications) (Ronchi et al., 2017).

3.3. *Findings of wildfire, pedestrian and traffic model reviews*

Different modelling tools and approaches for the representation of the three key modelling layers have been examined based on the systematic approach for the review. A set of common factors have first being identified as the basis for the three review areas, which were then specialized during the review process. Information included in the review indicates functionality/capacity identified. Actual model capabilities may extend beyond the information included – through recent developments, unpublished developments and/or developments published and not represented in this analysis. Both commercial and open-source models were evaluated.

3.3.1. *Wildfire model review*

The analysis of wildfire models was conducted firstly by analysing the key sub-models included in such type of models (e.g. sub-models representing key variables such as rate of spread, spotting, smoke and fire intensity, etc.). This was followed by examining a selection of the most commonly used wildfire models along with previous existing wildfire model reviews (Sullivan, 2009a, 2009b, 2009c).

The characteristics of eight wildfire models were reviewed to assess their suitability for an integrated WUI fire evacuation modelling framework: Spark (Miller et al., 2015), FARSITE (Finney et al., 1998), Prometheus (Tymstra et al., 2010), Phoenix (Chong et al., 2012), WFDS/FDS (Mell et al., 2009), FIRETEC (Linn and Cunningham, 2005), WRF-FIRE (Coen et al., 2013), and CAWFE (Coen, 2013). These models have been selected given their availability, continuous development and range of modelling assumptions. The wildfire models used by fire and emergency agencies (commonly called operational fire models) include empirical and semi-empirical approaches such as FARSITE, Prometheus, Phoenix for the US, Canadian, and Australian vegetation. These wildfire models are regionally segregated, but have been tested on cross-border vegetation; for instance, FARSITE (tested in South America- Chile, Argentina; Mediterranean; and South African vegetation), Prometheus (tested in Alaska, USA; New Zealand; and Tasmania, Australia), Phoenix (tested in France and Turkey). While wildfire models based on physics (like WFDS/FDS, FIRETEC, etc.) are applicable to any vegetation, their use is limited by their computational cost. WRF-FIRE and CAWFE are coupled weather-wildfire models which make use of weather prediction models so that simulated atmospheric conditions direct the speed and direction of the wildfires.

The regional dependence of the operational models is quite significant, suggesting it may be difficult to have a general empirical or semi-empirical based wildfire model due to huge variation in vegetation internationally. However, these models can be modified to account for differences in vegetation. A flexible wildfire model like Spark (Miller et al., 2015) which allows the user to use their regional/vegetation based empirical or semi-empirical model can be an alternative to overcome this regional segregation, although the model requires further testing by considering for instance a comparison with other

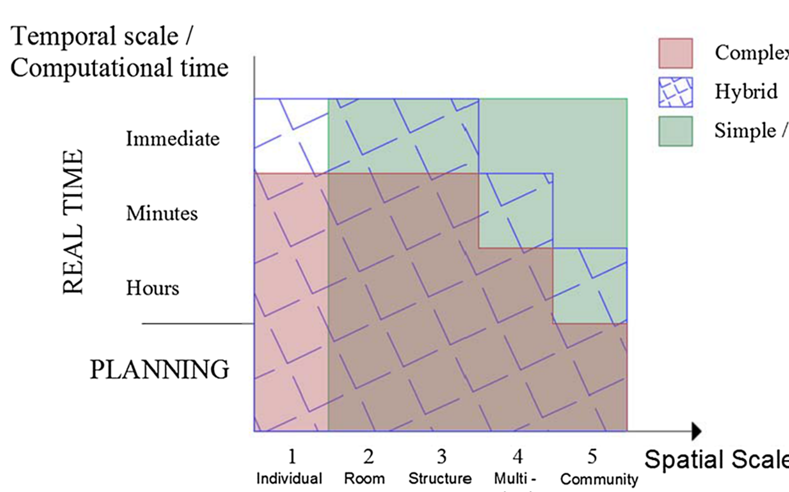

Fig. 5. Suggested model application scales given model refinement for pedestrian models. The spatial scale for the pedestrian models is divided into five categories and they are related to the temporal scale of the event (for both real-time and planning applications) (Ronchi et al., 2017).

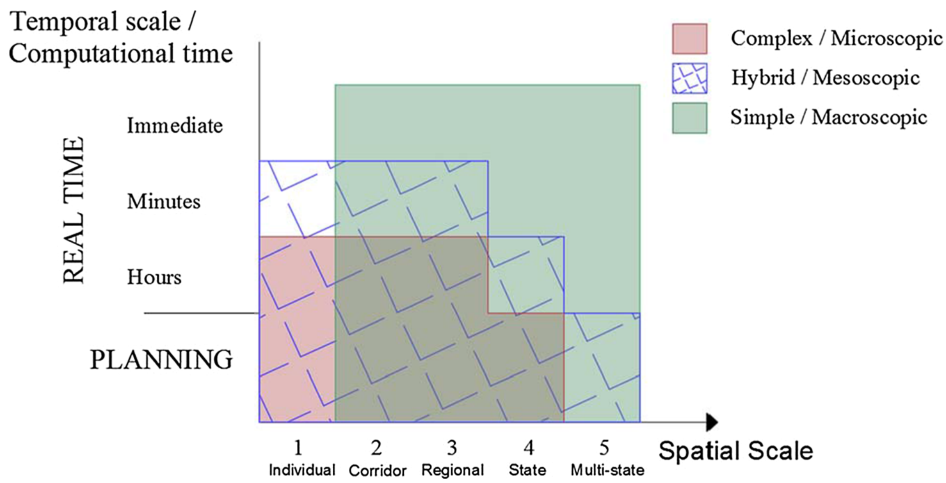

Fig. 6. Suggested model application scales given model refinement for traffic models. The spatial scale for the traffic models is divided into five categories and they are related to the temporal scale of the event (for both real-time and planning applications) (Ronchi et al., 2017).

Table 3
Comparison of wildfire model reviewed.

Wildfire model	Access to research community	Flexibility for modification	Computational resources required for simulating a typical 1 km × 1 km vegetation	Application of the model outside the country of development	Support & improvement by the developer
Spark	OA~	Yes	Low	Yesˆ	Yes
FARSITE	OA-OS	No	Low	Yes	No
Prometheus	OA	No	Low	Yes*	–
Phoenix	Commercial	No	Low	Yes*	–
WFDS/FDS	OA-OS	Yes	High	Yes	Yes
FIRETEC	NOA	–	High	Yes	–
WRF-FIRE	OA-OS	–	High	Yesˆ	Yes
CAWFE	NOA	No	Moderate-High	Yes	No

OA, OS, NOA means open access, open source, and not open access.
~OA maybe available to research community on research tie-up with the developer otherwise it is commercial.
ˆnot applied yet but the work is ongoing.
*few cases from countries outside of its development refer to evaluation report.
-no details available.

operational models. It should be noted that the three operational wildfire models reviewed have a prediction error of ~40% regarding the rate of spread (Cruz and Alexander, 2013). This error may allow the model to be used to study or decide evacuation trigger points, but it leads to intrinsic limitations for integration applications. Physics-based wildfire models can be applied more broadly and may be able to reduce inaccuracy for homogenous vegetation. However, their deterministic nature and computational expense mean that operational use may still be a challenge. A summary of the comparison of wildfire models reviewed is presented in Table 3.

The wildfire model review allowed the identification of a set of 17 questions which can be used to assess the suitability of any existing or future wildfire model for the proposed integrated modelling framework in relation to the scenarios under consideration. These questions are presented in appendix 1 and are associated with a detailed list of related sub-questions which are presented in the full report of the project (Ronchi et al., 2017).

3.3.2. *Pedestrian model review*

Pedestrian models were examined according to two distinct evacuee responses to a wildfire that need to be represented: (1) pedestrian movement to a place of safety or movement to an intermediate location directly on foot, and (2) pedestrian movement to a private or shared vehicle which will then carries them to a place of safety or intermediate location. Places of safety might include official places of refuge (e.g. designated shelters) or informal locations (e.g. the home of a family member). It is recognised that pedestrian movement may only be of secondary interest during most large-scale WUI incidents. However, pedestrian movement is a key input into the traffic system – as precursor to the arrival of vehicles in the traffic assessment.

A staged approach was adopted using existing model reviews as starting source material (Gwynne et al., 1999; Kuligowski et al., 2010) for both the assessment of pedestrian model functionalities. During the first stage, the models were flagged according to whether they insufficiently addressed one of the categories identified in a previously defined model review template. This 'cut' was performed in conjunction with the potential application types: primarily, planning (constraints led by the naturalism of the representation) and real-time (constraints led by representative expediency and model performance). The set of models was then reduced by reviewing these criteria and excluding models that were not able to meet all of them. In some cases, a model was only excluded because of the set of criteria marginally not met, rather than one criterion definitively not met. The remaining models were then reviewed according to a broader set of criteria (i.e. the identification of the benchmark features of a pedestrian evacuation model for WUI fire evacuation). These criteria were initially selected from those employed in previous model reviews but evolved as the models were examined in conjunction with expected WUI timelines/events, system requirements and output requirements (Gwynne et al., 1999).

An overview of the model capabilities in regard to the proposed WUI integrated model is shown in Table 4. The full set of results is then indicative of current capabilities. Based on the review, 20 questions concerning model capabilities needed for integration were derived and

Table 4
Summary of the reviewed characteristics of pedestrian evacuation models.

	Model Refinement	Model Interaction	Dedicated Sub-models	Model Output	Model Interruption	Model Configuration	Spatial Repres.	Max. Pop. Size	Max. Geometry	Behav. Elements	Model Run-time	Model Testing
EvacMod using ArcGIS Network Analyst[a]	S	FT	Y	O				50 k+	U			S
ASERI[b]	R	F	Y	OL		FG	U/C		>	R/T/D/F		D/E
EXODUS[c]	H	F	Y	OL	Y	FG	U/C	25 k+	U >	R/T/D/F	Y	D/E/S/3
CRISP[d]	H	F	Y	OL		G	U/C		>	R/T/D/F		D
EPT[e]		F	Y	OL		G	U/C	80 k+	>	R/T/D/F		D
EvacuatioNZ[f]	S	F	N	OL		FG	U/C		>	R/T/D/F	Y	T/E/S
EXIT89[g]	S	F	Y	OL		FG	U		>	R/T/D/F	Y	D/3
FDS-Evac[h]	R	F	Y	OL		FG	U	1 k	>	R/T/D/F	Y	D/E/3
Legion[i]	R	FT	Y	OL		G	U/C	50 k	U >	R/T/D/F		R/D/E/3
MATSim[j]	R	T		OL			U	450 k	U >	R/T/F		
Myriad II/UAF[k]	H	FT	Y	OL		G	U/C		U >	R/T/D/F		E/3
PathFinder[l]	H	F		OL	Y	FG	U/C	65 k	>	R/T/D/F	Y	R/D/E/S
PEDFLOW[m]		F	Y	OL		G	U/C		>	R/T/D/F		E
PedGo[n]	R	F	N	OL		G	U/C	700 k+	>	R/T/D/F	Y	D/E/S/3
Pedestrian Dynamics[o]	R		Y	OL	Y	FG	U/C	50 k	U >	R/T/D/F	Y	3

The abbreviations used in Table 4 are outlined here: Q1: S = Simplified; H = Hybrid; R = Refined, Q2: F = Fire; T = Traffic, Q3, 5–8, 10, 14, 15, 17, 20: Y = Yes; N = No, Q4: O = Overall; L = Local, Q9: F = File Format; G = via GUI, Q11: U = User-defined; C = CAD, Q12: Population Size, Q13: U = Urban-Scale; > Beyond/outside single structure, Q16: R = Route Use; T = Travel Speed; D = Delays; F = Flow Constraint, Q19: D = Drill; 3 = 3rd Party; E = Experiment; R = Real Incident; S = Simulated.

[a] Jones, JM, Ng, P and Wood, NJ, Pedestrian Evacuation Analyst – Geographic Information Systems Software for Modeling Hazard Evacuation Potential, 2014.
[b] http://www.ist-net.de/aseri/.
[c] https://fseg.gre.ac.uk/exodus/.
[d] https://www.bre.co.uk/page.jsp?id=269.
[e] http://www.regaldecision.com/crowd_management.php.
[f] https://evacuationz.wordpress.com/.
[g] http://www.iafss.org/publications/fss/4/657.
[h] http://virtual.vtt.fi/virtual/proj6/fdsevac/documents/FDS+Evac_webpages.pdf.
[i] http://www.legion.com/.
[j] http://www.crowddynamics.com/products/uaf.php.
[k] Meister, K., Balmer, M., Ciari, F., Horni, A., Rieser, M., Waraich, R. A., & Axhausen, K. W. (2010). Large-scale agent-based travel demand optimization applied to Switzerland, including mode choice.
[l] http://www.thunderheadeng.com/pathfinder.
[m] https://arxiv.org/abs/1508.06785.
[n] http://traffgo-ht.com/en/pedestrians/products/index.html.
[o] http://www.pedestrian-dynamics.com/.

they are outlined in Appendix 1 (also in this case, they are associated with a detail list of sub-questions presented in the full report of the work (Ronchi et al., 2017)). Only the questions posed that produced significant variation between the models examined are reported here. The reader is referred to the original report for the complete review.

3.3.3. Traffic model review

Traffic models are here intended as models that represent vehicles on the road in WUI fire evacuations. While traffic modelling in this instance mainly refers to evacuation, it can also be used to represent the transport of emergency responders in their efforts of suppression of the fire. To understand the methods used for the definition of the requirements for the integration of traffic model in a multi-physics framework for WUI fire evacuation, a detailed analysis of the existing sub-models and approaches employed for the simulation of traffic has been performed. Following this analysis, the models under consideration are divided into two subsets: (1) traffic models that are specifically designed to address the evacuation problem, and (2) generic traffic simulation models. These later models are included since they could potentially be used for evacuation purposes.

Based on the features required in traffic models for the simulation of WUI fire evacuation and coupling with other modelling layers, a set of existing models have been reviewed. The review was performed in several steps, namely:

- Identification of the key features (for general traffic simulations) and variables (specific to traffic evacuation) useful for the representation of WUI fire evacuation within traffic models
- Review of a list of selected traffic models adopting different approaches

For each model, a set of selected features and variables of interest for wildfire evacuation were assessed by collecting information from research papers (on-line documents, developers' websites, and user manuals/technical references). In most instances, the model developers themselves provided feedback on the review performed.

Models were classified according to the type of traffic modelling approach adopted (macroscopic, microscopic, mesoscopic), possibility to simulate dynamic processes, and a list of traffic modelling-related variables (Barceló, 2010):

- Demand-side variables (demographic data, background traffic, travel demand patterns);
- Supply-side variables (capacity, speed, flow direction);
- User-side variables (driving behaviour, headway, acceleration, reaction time, route choice);
- Dynamic variables (traffic management, dynamic road infrastructure, adaptive choice behaviour, people compliance, real-time instructions).

Traffic models should also address ingress attempts, as human response during WUI fire scenarios may include people trying to enter the hazard zone as well as leaving it (Wilkinson et al., 2016). In addition, the use of activity-based modelling (e.g. Van der Gun et al., 2016) may help in representing trips inside the evacuation area, which are not evacuation-related (e.g. collecting/escorting passengers, returning home, etc.). Moreover, the representation of background traffic gives the opportunity to include other types of journeys (Murray-Tuite and Wolshon, 2013) (e.g. representing peak traffic level scenario, shadow evacuation, etc.), which may affect the road network capacity during the evacuation.

Given the larger literature available on traffic modelling, detailed information concerning the review of traffic models can be found in a dedicated publication on this issue (Intini et al., 2019).

The review showed that some of the existing traffic models are able (explicitly or implicitly) to represent many of the variables concerning WUI fire evacuation scenarios. Nevertheless, it appears evident the need for a dedicated modelling framework able to integrate results from other models. Similar to the approach used for the other model reviews, the last step included the identification of a set of 21 questions to be asked to traffic models to evaluate their features for an integrated WUI fire evacuation modelling framework (see Appendix 1). The authors refer to the full report of the work for further details on the sub-questions associated with them (Ronchi et al., 2017).

4. The WUI fire evacuation modelling framework

This section presents the proposed multi-physics modelling tool which integrates the three main layers of WUI fire evacuation scenarios. The required data exchange between different modelling layers are discussed along with suggestions on the system specification of the modelling framework.

4.1. Required data exchange

The assessment of the required inputs/outputs exchange between models is based on (a) the model reviews and the current modelling capabilities, and (b) the examination of previous incidents and background material (i.e. how in reality these domains influence each other). Only the primary modelling elements are here discussed, rather than the secondary elements that, although important, can be indirectly represented by the primary elements or included in other external datasets or models. For example, the actions of emergency responders are not included in Table 6 but can be instead implicitly represented in the wildfire model through the impact of these actions on the development of the fire. The "other" category in refers instead to all remaining models and data which should be considered in a WUI evacuation scenario (e.g. weather models, topological data, vegetation classification type, etc.).

For instance, the *Wildfire* model is deemed to affect both the *Pedestrian* and *Traffic* models in some way (see row 1, in Table 6). The first column of results shows that the output from *Traffic* and *Other* model has an impact on *Wildfire* models. The present work identifies the mutual relationships between models at a higher level as well as identifying the required data exchange and communication that should be included in an integrated system.

The model information exchange (the nature of the inputs/outputs) can be presented in different formats:

(1) numerical results [N] (e.g. the evacuation was completed in X seconds),
(2) graphical results [G] (e.g. an image of the congestion produced on a particular route),
(3) tabular results [T] (e.g. a table showing the vehicle numbers at several junctions within several time windows),
(4) qualitative (or descriptive) results [Q] or geospatial [GS] (e.g. a GIS map of the area impacted by the fire front or the routes adopted by pedestrian and vehicle traffic),
(5) animated results expressed as a time-based sequence of numerical instances [A] (e.g. the evolution of the traffic queue at a particular junction over time).

A legend using the initial letter of each data format within brackets is used after each inputs/outputs for exchange is presented. The variables listed in Table 5 refer to the information provided by a source model (identified in column 1) as an output that affects the initial conditions of a sink model (identified in row 1). There are also a number of interactions between external *'Other'* models that are not presented in Table 5. The identification and analysis of these interactions are out of the scope of the present work, thus they have been left out of this paper.

The integration between models may take place in different

Table 5
List of required data exchange between wildfire, pedestrian, traffic and other models.

Modelling component	→Wildfire	→Pedestrian	→Traffic	→Other
Wildfire→	x	Data affecting pedestrian movement [N, G, Q] Condition of evacuation routes [N, G] Status of structures of interests [G, Q] Access to communication and communication utilities (e.g. internet connection, mobile phone signal, etc.) [N, Q] Available cues for pedestrian risk perception [N, Q]	Road network accessibility and capacity [N, G, Q] Transportation mode availability [Q] Status of structures of interests [G, Q] Vehicle availability [Q] Data affecting route availability, selection and driving performance [N, G, Q] Available cues for risk perception affecting driver choices [Q]	x
Pedestrian→	x	x	Pedestrian location during the event [N, G, Q, A] Pedestrian arrival times to vehicles [N, G, A] Departure time from vehicle (i.e. time for the decision to evacuate plus the time to walk to the vehicle) [N, G, T, A] Boarding time of a vehicle [N, G, A] Status of pedestrians (e.g. injuries) [G, Q]	x
Traffic→	Traffic congestion affects land fire- fighting [N, T, A]	Vehicle availability to pedestrians [N, G] Public transport availability [G, Q] Vehicle location during the event [N, G, T, A] Accessibility, capacity of vehicles, current occupancy level [N, G, A] Vehicle boarding time [N, T, A] Status of vehicles [N, G, A] Vehicle performance [N]	x	x
Other →	Fuel data [N, G, GS, T] Weather conditions [N, G, GS, A] Geographical information [N, G, GS]	Initial population size [N, G, A] Pedestrian initial location [N, G] behavioural response model affecting pedestrian evacuation decision [Q] behavioural response model affecting departure time [N, G, T] Status of pedestrians [Q, A] Type of terrain from GIS models [N, G, GS] Impact of emergency response intervention [N, G, GS, A]	Network configuration [N, G, GS, Q] Initial location and properties of vehicles [N, G, GS, Q] Available modes of transport [N] Availability of road network [G, GS] Background traffic [N, G, GS, T, A] Rescue service [G, Q, A] Weather conditions [N, G, GS, Q, A] Traffic management measures [G, Q]	Out of the scope of this work

manners in relation to the host environment and the implementation of the layers. The present study suggests that regardless of the starting modelling environment used for the integration, the listed data exchange should be ensured.

4.2. Schematic flow-chart of the framework

A set of basic system architectural components are required to produce the information exchange above presented, thus a set of suggestions for such architectural components are given in Table 6.

The components identified would allow external information (both reported and from users) to be implemented into the system. This information is then processed and assessed to determine user access rights and viability, and then scenarios are generated in a format suitable to configure the internal models. These scenarios, the time constraints and the computational resources available would need to be assessed to determine which models should be executed or databases interrogated. In some instances, certain models / sub-models might be turned off

Table 6
Basic description of system architecture.

Name	Component purpose
External data/information sources	Sources that provide input to the system, but that are not directly under the control of the proposed system; e.g., sensors, field reports, social media, etc.
External systems	Systems/models/platform that receive output from the system as end users that are not under the control of the proposed system; e.g. third-party software, databases, handheld devices, worn devices, mounted devices, etc.
(Graphical) user interface	Means by which users receive and/or provide information in accordance with their security and access rights. May take the form of a graphical interface or be template or machine driven
Inbound information management	Layer to process data/information provided by external sources
Communication layer	Layer to manage information provided by or to users via Graphical User Interface (GUI)
Outbound information publisher	Layer that formats output generated by the simulation system
Administrative server	Component that determines user access and request viability given user access rights, the information available, timing, etc.
Data store (long-term and temporary)	Component that stores (local or remote) results for future user or system access
Web information management	Component that determines/prioritizes scenarios of interest to be examined and access to simulation system given external user/system/ sensor information
Model scenario generator	Layer that converts external scenario information into model configuration and execution instructions
Model execution manager	Component assesses scenarios of interest, determines the combination of models to be executed and configures models accordingly. Depending on the approach adopted, the selection and the execution of the models may be performed by separate components
Subject domain models	Wildfire/pedestrian/traffic models
Simulation database	Store of historical simulation results
Results assessor	Component examines results produced to determine whether they should be relayed to external users/stored
Model results alignment	Component that aligns results from different domains and different approaches (e.g. event-based or time-based)
Decision support	Possible additional stage where implications of results are interpreted

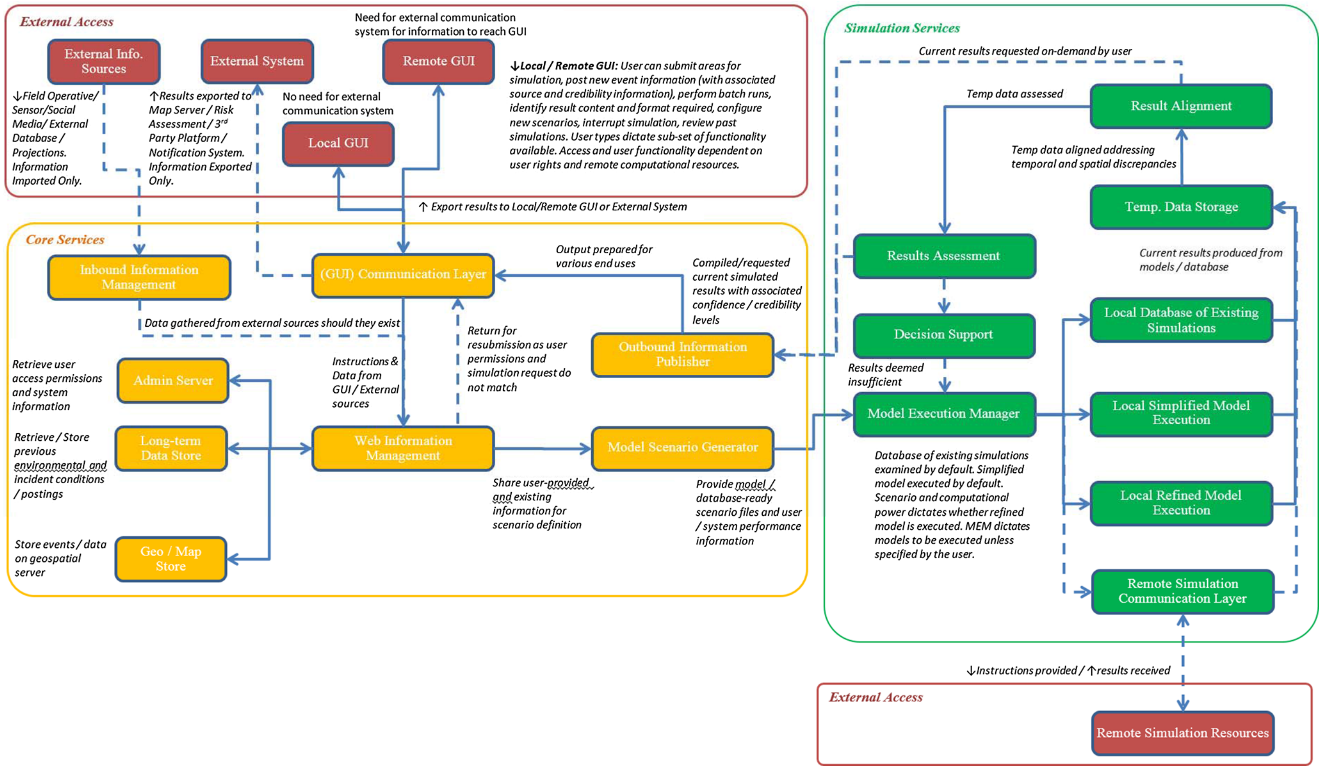

Fig. 7. Simple System Architecture with decision support sub-module for a proposed WUI model.

given lack of external information or computational constraints. The results generated would then be examined to determine whether they are suitable for the user's needs and then the results returned for review or further model runs completed. The results would then be stored and returned to the user in the desired format.

An example system architecture capable of this process is shown in Fig. 7. This should be considered as an informal description. For such a model to be implemented, a formal description of the users, use cases, system components, system work flow, etc. would be required specified in a standard format such as UML (Unified Modelling Language). It should be noted that the platform is intended to be model agnostic; i.e. ideally it should be designed in order to be able to make use of outputs from different models. This is extremely important for instance for the case of wildfire modelling, given the fact that certain wildfire models may be more commonly used in certain regions (due to a specific type of vegetation for instance).

5. Discussion

The two main applications of the proposed simulation system are the prediction of evacuation performance for: (1) real-time decision support and (2) evacuation planning. Real-time decision support applications mostly relate to the assessment of the need to evacuate an area *during an incident*. This is best understood through the study of the evolution of fire perimeters (Taylor and Alexander, 2016) and possibly identifying trigger points (Dennison et al., 2007); i.e. points that indicate the need for evacuation. Hazard maps have been looked at by stakeholders often in a skeptical manner due to the fact that maps may be out of date (i.e. reliant on old data), incomplete or inconsistent (Nunes et al., 2017). The starting point of this work is that, as we move forward, there will be more (and more reliable) information and analytical / simulation tools will be available (with higher computational power) to allow for an updated understanding of current WUI fire evacuation events both in real time as well as giving the opportunity to better assess vulnerability in relation to different scenario conditions for evacuation planning.

Decision making in WUI fire evacuation scenarios is heavily reliant on the information available; i.e. the evidence on which the WUI response is based. The emergency response to WUI fires includes the ability of the affected community to prepare for the hazards, adapt to the evolving conditions of the incident and recover from disruptions in the immediate aftermath of the incident. To ensure that this preparation and response is adequate, the effectiveness of the pre-incident decisions and decisions taken during the incident needs to be understood in order to allow assessment of these decisions before they are finalised; i.e. before they are put into practice. Both design and emergency response are key elements in addressing the occurrence, development and impact of WUI incidents. Efforts to inform and improve these elements will impact the frequency and severity of such WUI incidents. This work addresses this need by presenting a system specification for a toolkit able to provide numerical evidence to support the design and emergency response processes. The framework presented here is intended to be generally applicable, given the wide range of regional and national end users around the world that might benefit from such tool. Nevertheless, there are some challenges that need to be addressed in order for it to be broadly applicable. For instance, some of the modelling layers might rely on regionally-specific data (e.g. vegetation, resident response or type of road networks might be different). A possible solution to this issue is to apply the framework in a modular way, so that suitable modelling tools could be applied in relation to the region of interest, along with the data provided.

The assessment of the required level of model scope and refinement highlights the (a) importance of accurately denoting model refinement and (b) the relationship between this refinement and the generated results. It should be noted that the recommendations for different levels of refinement should not be purely based on the assessment of the tool for an individual subject domains (wildfire, pedestrian, or traffic). It should address instead the sensitivity of the overall results of the influence of one modelling domain on another. This means that the propagation of inaccuracies between models should be examined, along with the potential wastage of dedicating resources in the more refined representation in one domain that is then not reflected in an adjacent area (or the projected results). In other words, the developer/user should aim for a *consistent level of crudeness* to avoid discrepancy in the resolution of the modelling results, as well as the propagation of uncertainties.

The list of outputs and inputs for exchange between different modelling layers are reported to inform the development of a comprehensive multi-physics tool. An indication of the data format for the relationships outlined was presented. While assessing different types of models, it has been possible to identify the main requirements for data exchange between the three different types of models (wildfire, pedestrian, traffic) as well as other external models/information (e.g. weather conditions). In addition, key modelling gaps have been listed (Ronchi et al., 2017). The most important gaps refer to sub-models able to represent different variables concerning the impact of vegetation management, uncertainty associated with fire perimeters estimation smoke/firebrand spread sub-models. Other key gaps include the need for a comprehensive model for human response in case of WUI and sub-models able to better represent choices in relation to different conditions (e.g., dynamic traffic signage, information available) and the impact of emergency responders. The most important data gaps relate to the validation of the sub-models for wildfire modelling (e.g. smoke and spotting) and data about human behaviour, e.g., route/destination choices, driving behaviour and driving compliance to information. For example, evacuees might have limited, inconsistent experience or conflicting information and in such circumstances it may prove more difficult to predict response. Therefore, future research should investigate human behaviour in different conditions and under different available information (in line or not with experience or without information).

The key outcome of the present work is the need for a paradigm shift in the future modelling tools to be used for informing decision making in WUI fire evacuation scenarios. In fact, while existing modelling tools mostly rely on risk mapping based on individual layers considered in isolation (generally based on fire hazard) (Calkin et al., 2011; Dillon et al., 2015), the proposed integrated multi-physics tool would enable the assessment of vulnerability. The proposed system would in fact allow vulnerability mapping given the integration of different layers into a single tool. Such tool would allow to evaluate the relationships between fire-related hazards in conjunction with the pedestrian- and traffic-related issues, such as road network capacity and characteristics and the population under consideration.

6. Conclusion

WUI incidents can be extremely complex and dynamic - involving many structures, locations, and organisations in a short-period of time. To successfully respond to such incidents those involved must have an understanding of current and near future events that affect them (or those for which the individual has responsibility) in order to safeguard against such threat. Efficient information sharing is crucial to enable informed decision-making, and special attention should be paid to the critical information needs and the quality of that information. Currently, the situational awareness of responders and residents typically consists of static information or dynamic information up to a recent (assumed current) point in time. The work presented here is based on the assumption that these decisions would benefit from a broader range of information that can be projected beyond the current conditions. For this reason, the proposed framework includes wildfire, pedestrian and traffic modelling components.

The intended (and generated) outcomes of this work was (a) a specification of a suite of simulation tools enabling a system to be developed that can make relevant forecasts regarding the progress of an incident and the effectiveness of pedestrian and traffic responses according to the time and information available; (b) a set of questions for future designers to ask of candidate models being considered for inclusion within such a system, (c) the identification of research gaps in modelling capabilities. We are advocates of the simulation process and the insights that it can provide during the planning phases (i.e. seeing the impact of design change before it is implemented) and during the response phases (i.e. seeing the impact of the decision before it is enacted). Any simulated results should always be placed in context - to the modelling assumptions on which it is based, the data available and the target scenario. The results will always only produce additional evidence and guidance to complement the human decision-making process. However, such evidence can produce invaluable insights that might otherwise not otherwise be available (given issues of complexity, scale, diverse expertise, and ethical concerns) and for that reason alone such tools should be explored to determine their benefits.

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Appendix A. Questions to assess model suitability to an integrated tool

In the following questions, those marked [E] are essentials, while those marked [D] are desirables.

Questions concerning wildfire models

- Q1 [E] Can the model operate at (a) a simplified (e.g. empirical) level, or (b) using a hybrid (e.g. semi-empirical) approach, or (c) using a physics-based approach?
- Q2 [E] Can the model receive input from external sources/systems/models?
- Q3 [D] Does the model include dedicated sub-modules to represent the effect of information from external models/sources?
- Q4 [E] Does the model provide output on the overall outcome, local conditions (i.e. at different levels of refinement), evolving dynamic/static information, and/or reflect specific events of interest (e.g. containment of fire)?
- Q5 [D] Can end users access the model as required?
- Q6 [D] Can the model be interrupted, reconfigured and restarted to allow new field/user reports on conditions to be considered within the simulation?
- Q7 [E] Can the model initial conditions (fire behaviour model/vegetation/wind conditions) be user-configured to represent the scenarios of interest?
- Q8 [D] Can the model output be user-configured?
- Q9 [D] How does the user/*equivalent external system* configure the model?
- Q10 [E] Can the user specify the area of interest to be simulated?
- Q11 [E] Does the model allow for spatial geometries to be generated by the user *(or equivalent external system)* or provided through a non-

proprietary file format?
- Q12 [E] Is the maximum topographical size that can be represented sufficient for the scenarios of interest?
- Q13 [E] Is the vegetation/terrain sufficiently diverse for the scenarios of interest?
- Q14 [E] Can the model be run within the desired timeframe
- Q15 [D] What platform is required to execute the model to facilitate desired performance?
- Q16 [E] What evidence is available describing previous model testing?
- Q17 [E] Is the model currently available, accessible and supported by the model developer?

Questions concerning pedestrian models

- Q1 [E] Can the model operate at (a) a simplified (e.g. empirical, flow) level, (b) a refined (e.g. agent-based) level, or (c) using a hybrid approach?
- Q2 [E] Can the model receive input from external sources/systems/models?
- Q3 [D] Does the model include dedicated sub-modules to represent the effect of information from external models/sources?
- Q4 [E] Does the model provide output on the overall outcome, local conditions (i.e. at different levels of refinement), evolving dynamic/static information, and/or reflect specific events of interest (e.g. a congestion level is reached)
- Q5 [D] Can end users access the model as required?
- Q6 [D] Can the model be interrupted, reconfigured and restarted to allow new field/user reports on conditions to be considered within the simulation?
- Q7 [E] Can the model's initial conditions (geometry/population/response) be user-configured to represent the scenarios of interest?
- Q8 [E] Can the model output be user-configured?
- Q9 [E] How does the user / *equivalent external system* configure the model?
- Q10 [E] Can the user specify the area of interest to be simulated?
- Q11 [E] Does the model allow for spatial geometries to be generated by the user *(or equivalent external system)* or provided through a non-proprietary file format?
- Q12 [E] Is the maximum population size that can be simulated sufficient for the scenarios of interest?
- Q13 [E] Is the maximum geometry size that can be represented sufficient for the scenarios of interest?
- Q14 [E] Is the population sufficiently diverse for the scenarios of interest?
- Q15 [E] Is the geometry/terrain sufficiently diverse for the scenarios of interest?
- Q16 [E] Can the model represent core evacuee behavioural elements: route use, travel speed, delays, flow constraints?
- Q17 [E] Can the model be run within the desired timeframe?
- Q18 [D] What platform is required to execute the model to facilitate desired performance?
- Q19 [E] What evidence is available describing previous model testing?
- Q20 [E] Is the model currently available, accessible and supported by the model developer?

Questions concerning traffic models

- Q1 [E] Which modelling approach is employed by the model (macroscopic, mesoscopic, microscopic, integrated). Is the modelling approach suitable for the scenarios under consideration?
- Q2 [E] Can the model receive input from external sources/systems/models?
- Q3 [D] Does the model include dedicated sub-modules to represent the effect of information from external models/sources?
- Q4 [E] Does the model provide output on overall outcome, local conditions (i.e. at different levels of refinement), present dynamic/static information, and/or reflect specific events of interest?
- Q5 [D] Are the expected end users able to configure the model given the means provided?
- Q6 [D] Can the model be interrupted, reconfigured and restarted to allow new field / user reports on conditions to be taken into account?
- Q7 [E] Can the model's initial conditions (road network / background traffic) be user-configured to represent the scenarios of interest?
- Q8 [E] Can the model output be user-configured?
- Q9 [E] How does the user configure the model?
- Q10 [E] Does the user specify the area of interest?
- Q11 [E] Does the model allow for geometries to be generated by the user or provided through a non-proprietary file format?
- Q12 [E] Is the maximum number of vehicles that can be represented sufficient for the scenarios of interest?
- Q13 [E] Is the maximum size of the area sufficient for the scenarios of interest?
- Q14 [E] Is the represented traffic sufficiently diverse for the scenarios of interest?
- Q15 [E] Is the geometry / terrain sufficient diverse for the scenarios of interest?
- Q16 [E] Can model represent core evacuee behavioural elements: e.g., route choice, driving speed, etc.?
- Q17 [E] Is the model based on a trip-based (movement from point A to B) or an activity-based approach? Is the model able to simulate intermediate destinations?
- Q18 [E] Can the model be run within the desired timeframe?
- Q19 [D] What platform is required to execute the model?
- Q20 [E] What evidence is available describing previous model testing?
- Q21 [E] Is the model currently available, accessible and supported by the model developer?

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