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Report 3256

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Abstract. This technical note presents a brief overview of the models available for the simulation of fire evacuation at the wildland-urban interface in touristic areas. Depending on the scale of the scenarios under consideration and the evacuation mode considered, models are split into macroscopic vs microscopic tools and 1) pedestrian models, 2) traffic models, 3) coupled evacuation models, 4) modelling unconventional evacuation modes. The key findings of this review are: 1) When pedestrian movement is the main mode of evacuation transport, the scale of the analysis will have a strong impact on the choice of the most appropriate modelling approach although at building scale and not very large area size, the use of microscopic modelling based on a continuous approach seems to be a suitable method. 2) When multiple modes of transport are considered (e.g., pedestrian and traffic), the modeller should make a call into modelling explicitly or implicitly the pedestrian response and movement layer, 3) most evacuation models are currently not able to model explicitly unconventional means of evacuations such as displacement via sea or air. The scenario complexity and the uncertainty in the available input will affect the choice of modellers to represent evacuation modelling layers (e.g., pedestrian response, pedestrian movement, and traffic movement) and their interaction with the wildfire explicitly or implicitly.

Wildland-Urban Interface Fire Touristic Infrastructure Protection Solutions

WUITIPS

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Evacuation modelling for Wildland-urban Interface fires in touristic areas

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1. Background

The WUITIPS project aims at harmonizing procedures and approaches concerning fires in touristic areas at the wildland-urban interface. In this context, human vulnerability plays an important role and is object of a dedicated work package (Work Package 5). One of the key issues associated with human vulnerability is the assessment of possible responses and behaviour in case of a wildfire evacuation (Haghani et al., 2022). To date, several modelling tools and approaches exist to perform such type of analysis (Ronchi & Gwynne, 2019). Each tool presents its advantages and limitations and may be suitable for use in relation to the scenario under consideration. A first step towards the use of evacuation modelling tools for wildfires in touristic areas is to assess the specific needed features (including transportation modes being modelled) in relation to different available modelling approaches. For this reason, part of the work package activities concerning human vulnerability in the WUITIPS project relates to a review of the capabilities of existing evacuation modelling tools for the representation of different types of wildland-urban interface evacuation scenarios in touristic areas. This technical note summarises the findings of the work conducted on this issue and present the key results of this review.

Evacuation models can be used to estimate a range of outputs which are relevant to safety in wildland-urban interface fires. Evacuation times via different transportation modes are the key output of such models, and they are generally represented through the so-called evacuation time curves. These curves represent the time of arrival to a given safe destination (e.g., a shelter, an area which is not threatened by the fire) of all evacuees. It should be noted that not all people in a threatened community decide to proceed with evacuation (Blanchi et al., 2018) even in case of mandatory evacuation, therefore, evacuation models also generally take into account the percentage of people who decide to defend in place (Cova et al., 2009). Evacuation models could also provide specific information related to the transportation mode they simulate. This for instance relates to the distance covered by evacuees (e.g., on foot or using a vehicle) and their adopted routes. This information could be particularly valuable to assess the fire hazard exposure and in turn perform an assessment of human vulnerability. Additional outputs that could be obtained by evacuation models relate to shelter usage and the identification of the impact of evacuation orders (e.g., mandatory vs voluntary evacuation vs defend-in-place) and what-if scenarios on overall human safety.

2. Goal and Objectives

A literature review concerning the use of modelling tools for the simulation of evacuation at the wildland-urban interface has been performed. The main goal of this work is to aid potential model users in identifying the most suitable approach in relation to the type of scenarios under consideration and the scope of their analysis (i.e., evacuation planning or emergency management). In this context, the main objectives of the review were to 1) to identify different types of models in relation to the evacuation mode under consideration, 2) to identify the key modelling inputs required for the representation of the evacuation of people in the wildland-urban interface in touristic areas, 3) to provide an overview of the capabilities of the main available evacuation models to simulate evacuation with different transportation modes, 4) to discuss the relationship between the granularity of the model (e.g. microscopic vs macroscopic), the uncertainty in the inputs and the scale of the scenario under consideration 5) to provide recommendations for future model improvements in relation to their application in the context of wildland-urban interface in touristic areas.

3. Methods

It should be noted that this work is largely based on a set of recent reviews and documentation in this domain. These include:

1) Ronchi, Enrico, and Steven Gwynne. 'Computational Evacuation Modeling in Wildfires'. In Encyclopaedia of Wildfires and Wildland-Urban Interface (WUI) Fires, edited by Samuel L. Manzello, 1–10. Cham: Springer International Publishing, 2019. https://doi.org/10.1007/978-3-319-51727-8_121-1.
2) Intini, Paolo, Enrico Ronchi, Steven Gwynne, and Adam Pel. 'Traffic Modeling for Wildland–Urban Interface Fire Evacuation'. Journal of Transportation Engineering, Part A: Systems 145, no. 3 (2019): 04019002.
3) Ronchi, Enrico, Guillermo Rein, Steven Gwynne, Rahul Wadhwani, Paolo Intini, and Albin Bergstedt. 'E-Sanctuary: Open Multi-Physics Framework for Modelling Wildfire Urban Evacuation'. Quincy, MA (USA): Fire Protection Research Foundation, 2017.

The first document (Ronchi & Gwynne, 2019) introduces the different approaches that can be used for the representation of evacuation in wildfires. This is directly applicable also for wildland-urban interface scenarios. In particular, this document is useful to identify to which extent models are representing a given evacuation mode or set of behaviours implicitly or explicitly and how this is reflected in the approach adopted.

The second document (Intini et al., 2019) is a comprehensive review of the existing variables that can be represented in traffic models for the specific application of wildland-urban interface fire evacuation. It also discusses explicitly the applications related to evacuation planning or real-time decision support. This means that the review not only focuses on reviewing the main capabilities of these models, but it also provides specific information about their suitability for the scenarios of our interest.

The third document (Ronchi et al., 2017) presents a large overview of models and tools applicable in the domain of wildfire evacuation. It explicitly discusses all modelling layers involved in the representation of these scenarios (e.g., wildfire spread, pedestrian response and movement and traffic). Further information concerning the traffic component of this review can also be found in (Bergstedt, 2018). The aim of this work was indeed to pave the way towards coupling of different modelling layers for wildland-urban interface fire evacuation applications.

This technical note provides a summary of these documents and builds upon them to provide recommendations regarding the choice of the most suitable modelling approach in relation to the wildland-urban interface fire evacuation scenarios in touristic areas under consideration.

4. Delimitations

The present document is focused primarily on the use of evacuation models in touristic areas for two sets of scenarios, namely 1) evacuation on foot at relatively small scale (e.g., evacuation at building level or in relatively small outdoor areas such as a camping site) and 2) large-scale traffic evacuation via private vehicles (e.g., cars). The use of models for other unconventional means such as evacuation via sea, air or via public transport are at a relatively early stage of development, therefore are not treated in great detail in this report. Wildfire evacuation events involving unconventional modes of transport are associated with a range of factors, decisions and actions that may have not been observed otherwise. On this topic, the readers are referred to (Tyler, 2021) as this document provides information concerning the simulation of evacuation through alternative means of egress, such as evacuation via sea or air. As these scenarios are not as frequent as evacuation via conventional means (pedestrian or traffic movement), the information relates mostly to how to retrofit existing models to be able to use them for such scenarios and what requirements a modelling framework should have to be used in this context. Although such types of evacuation may occur in evacuation scenarios in touristic infrastructures, they are not deemed very frequent and are therefore not treated in detail.

It is not the intention of this document to recommend a given commercial or research model and therefore specific models may be mentioned but not addressed in detail. In contrast, this document is intended to provide information to model users on what types of modelling approaches are recommended for use in relation to the type of scenario under consideration. Information regarding different numerical tools used for evacuation purposes are available in the literature. These tools are documented and some of them have been benchmarked for different application cases at different scales (Gwynne et al., 2023; Jullien et al., 2022).

5. Pedestrian evacuation models

All evacuation scenarios involve to some extent pedestrian movement. This can relate either to the movement from a household or tourist infrastructure to a (private or public) transportation vehicle or evacuation to a safe place on foot.

Based on (Ronchi, 2020; Ronchi & Nilsson, 2016), most pedestrian models generally represent both key phases of an evacuation, namely pre-evacuation (the time before purposive movement towards a safe place) and movement (Purser & Bensilum, 2001). The pre-evacuation phase is generally represented through the use of pseudo-random sampling from distributions to account for behavioural uncertainty (Jullien et al., 2020; Ronchi, Reneke, et al., 2014; Smedberg et al., 2021) in the time needed to respond. More recent approaches attempt to represent the evacuation decision process in more detail (E. Kuligowski, 2020; E. D. Kuligowski et al., 2022; Lovreglio et al., 2015a, 2016), although their use is not yet mainstream since they require a much larger and more detailed set of inputs (data) when being calibrated.

Pedestrian models can also be classified in relation to the level of resolution they adopt in the representation of the space (Kuligowski, 2016), being either network-based or continuous. The former assumes that the space can be approximated with either a coarse or fine network, while the latter represents the space as is through a system of coordinates. Hybrid approaches also exist (Chooramun, 2011), although they are currently not widely used. This is despite their great potential for scenarios with varying complexity and in which different levels of resolutions may be needed such as pedestrian evacuation in the wildland-urban interface.

Another key assumption made by models relate to their way of representing people, either as individual entities or as an aggregate. Those are generally referred as microscopic or macroscopic approaches. There is also a hybrid approach, namely mesoscopic models (Contini, 2022), in which individual people can be tracked but many of their features and behaviours are treated at aggregate level (Adrian et al., 2019).

Movement modelling in pedestrian simulators include both the representation of route choice (also called tactical level of movement) as well as local movement. Regarding route choice, pedestrian models may adopt different assumptions such as shortest route, quickest route, user-defined or based on certain conditions (e.g., presence of a threat such as fire smoke. (Jullien et al., 2020; Ronchi & Nilsson, 2016). Such approaches can be implemented through different algorithms, with popular ones being variation of A* or Dijkstra algorithms (Bladström, 2017). Factors that are to date not explicitly implemented in route choice modelling include the impact of the heat from the fire (ambient air, ground), people carrying luggage, unsuitable clothing (exposed skin to the sun, to the heat of the fire, to burning firebrands, or not sufficiently covered if low temperatures at night or at altitude, etc.), unsuitable shoes (flip-flops, open shoes, especially if uneven, stony ground or in case of long travelled distances).

Local movement modelling can include a wide range of approaches, including agent-based modelling approaches (such as the steering model (Reynolds, 1999)), Newtonian models based on forces (Helbing & Molnár, 1995), social distance models (Wąs et al., 2006), optimal steps models (Seitz & Köster, 2012), cellular automata (Bandini et al., 2011; Kirchner & Schadschneider, 2002; Lovreglio et al., 2015b) or hydraulic models (Gwynne & Rosenbaum, 2016; Predtechenskii & Milinskii, 1978).

Pedestrian models may also implicitly or explicitly represent the interaction with a fire threat, such as the products of smoke (Dréan et al., 2018; Purser, 2008).

Similar to movement, human behaviour can be represented at individual or aggregate level depending on the type of approach adopted (macroscopic, mesoscopic or microscopic). It should also be noted that pedestrian models may either just represent movement between two points - origin and destination - or allow for the representation of more complex behavioural itineraries (explicitly) (Kuligowski, 2016). The user would have to make a call into what approach to use in relation to the information available on the people to be represented, therefore deciding if the behaviour of locals vs tourists can be represented explicitly or implicitly with different modelling approaches.

A recent survey identified over 70 pedestrian models which can be used for evacuation scenarios (Lovreglio, Ronchi, et al., 2020) and investigated how users select which model to use. The survey highlighted that users tend to choose model in relation to their verification and validation (Ronchi, Kuligowski, et al., 2014), the documentation associated with the model and the outputs provided.

In a touristic area, it is likely that there will be a great variation in the type of people needed to be represented, e.g., (first time or recurrent) tourists vs local. For this reason, the use of a microscopic model seems suitable for the representation of the variation in the physical and behavioural characteristics of evacuees. In contrast, a macroscopic pedestrian model can be used when the uncertainties in the type of population present in the scenario are very large, therefore not being able to identify a priori what type of population needs to be represented with a sufficient level of detail. Macroscopic models can also be useful to provide a rough estimate of the time needed to evacuate a given area and have the great advantage of being quick in providing results also for very large scenarios (large being intended in terms of area size, population size and temporal scale).

In summary, the selection of an appropriate pedestrian model would depend on the (temporal and spatial) scale of the scenario, uncertainty in the inputs, complexity of the layout of the area under consideration and the number and type of people that needs to be simulated.

6. Traffic evacuation models

Traffic models generally adopt a traditional four-step structure when representing movement of vehicles (Barceló, 2010). The four steps include:

1. Trip generation
2. Trip distribution
3. Modal choice/split
4. Traffic assignment

Steps 1 to 3 are generally referred as travel demand (see Figure 1).

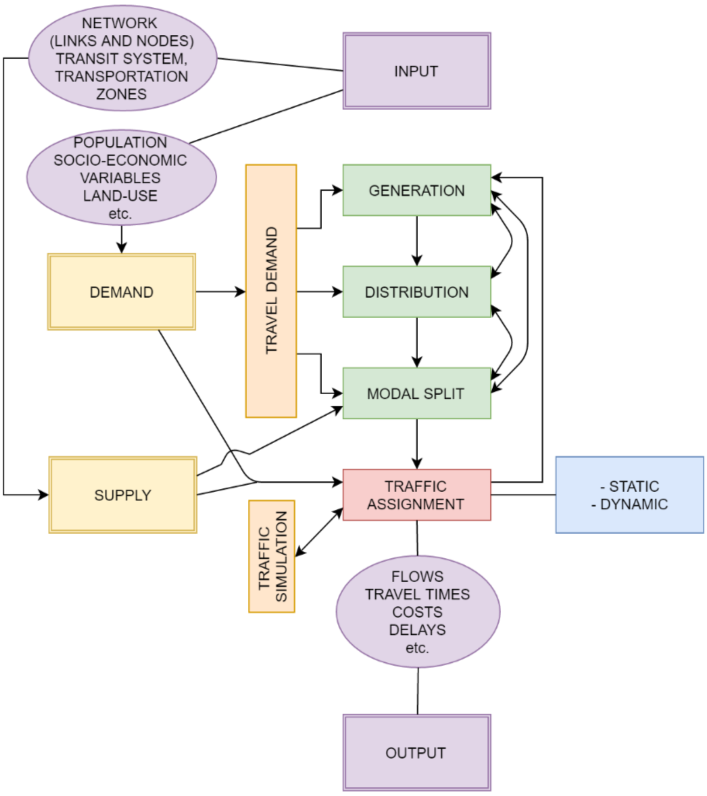

Figure 1. Schematic representation of four-step structure of models, from (Intini et al., 2019).

Trip generation refers to the total number of trips in each zone in a given time-period. In case of wildland-urban interface fire evacuation in touristic areas, this would include considering how many people are present in each accommodation or infrastructure in relation to the number of tourists present in the area. In addition, this can be used to consider implicitly the decision to stay or evacuate in relation to the information available (e.g., tourists may not necessarily have immediate access to all information e.g., regarding a mandatory evacuation order). Regional differences have also been shown in the so called “wait and see” response, thus meaning that a heterogenous population will likely include people exhibiting different behaviours (Vaiciulyte et al., 2022). The willingness of sharing resources may also affect the available transportation resources (Wong, 2019; Wong et al., 2021).Typical evacuation modelling approaches for trip generation include the representation of the binary choice between stay or evacuate (McCaffrey et al., 2018). It should be noted though that even the decision to stay may include some trips (such as reaching for family members) (Intini et al., 2019). A commonly used approach for the simulation of trip generation in evacuation in general and for wildland-urban interface scenarios is the use of random utility models (Kuligowski, 2020), which generally make use of logit structures to estimate the probability to evacuate among a given set of options (Lovreglio et al., 2016). In case of scenarios involving touristic areas, models should account for the variability in the information availability to different sets of people and calibrate models accordingly.

Trip distribution is used to predict the spatial patters or trips or other traffic flows between given origins and destinations. It can be represented with a trip-based or an activity-based modelling approach (Pel, 2017). In the trip-based models, the reference unit is the trip and the total demand of one-way evacuation trips is estimated at aggregate level (Intini et al., 2019). Factors which can be considered in this modelling approach relate to a set of population characteristics which are strictly relevant for the representation of locals vs tourists. This includes the availability of vehicles, experience with fires, purpose of the trip (e.g., reaching a shelter, searching for others, etc.). Activity-based models (Cascetta, 2009) estimate the number of trips by simulating the individual activities of each person. This means that rather than representing trips as a simple origin to destination movement, it is possible to identify a chain of trips (this could be exemplified with the equivalent concept of behavioural itineraries in pedestrian models). This approach would allow to represent explicitly joined trips by individuals in the same group. The main difference between these approaches is their ability to represent individual trips (Murray-Tuite & Wolshon, 2013). In case of no-notice evacuation (i.e. when the population has no information regarding the need to evacuate), the simulation of individual trips can play an important role since people may do several individual trips to gather people in their group (e.g. family members) (van der Gun et al., 2016). In the context of touristic areas, the cultural component is known to have an impact on the behavioural itinerary actions in wildfire evacuations (Vaiciulyte et al., 2021), meaning that tourists and locals may adopt different strategies depending on their immediate and long-term needs.

Modal split relates to the type of transportation mode being used during evacuation. Most models primarily represent evacuation through private vehicles. Vehicle availability plays a key role in the scenarios involving touristic areas, since not all tourists may have availability of a private vehicle to evacuate. In this case, publicly arranged transportation means may become the only option for such groups. Several modelling approaches exist for the representation of these scenarios, including descriptive, random utility and activity models (Intini et al., 2019). The probability of choosing a transport mode in a given period can be represented through its generalized cost in descriptive models. Random utility models generally perform this estimation through logit models (Cascetta, 2009), possibly considering how the transport modes can be grouped into categories (evacuation on foot, via public or private transportation means). Activity models would approach the problem by simulating individual mode choices. This can be performed for instance through probabilistic approaches (Castiglione et al., 2015). The representation of touristic areas exposed to wildfire risk may require a careful evaluation of the best manner to represent modal choice during evacuation given the specific characteristics that different people may have (locals vs first-time tourists, vs recurrent tourists), with private vehicle availability being a key aspect to be considered.

Traffic assignment can be represented with different levels of resolution in case of wildland-urban interface fire evacuation in touristic areas. The key aspects to be modelled include the representation of route choice, the simulation of traffic flows on the network and the interactions among evacuees (Intini et al., 2019). Two approaches exist in this domain, namely static or dynamic assignments. The static approach generally relies on the loading of an origin-destination matrix which refers to the scenario under consideration (generally a credible worst-case scenario). In contrast, the dynamic approach would consider the variability over time of traffic loading and route choices. For the scenarios under consideration in this work, a static approach may not be suitable (Pel et al., 2012), given the fact that conditions may vary substantially during the course of evacuation. For the case of touristic areas, tourists may be unfamiliar or have initially incomplete information concerning the routes to be used during the evacuation, thus making a dynamic approach more appropriate. It should also be noted that the wildfire threat may evolve over time (e.g. due to fire smoke (Intini et al., 2022)), thus making the conditions of the road network dynamic as well. Deterministic or probabilistic approaches can be used for the representation of route choice (Intini et al., 2019). Deterministic approaches solve the traffic assignment problem by reaching an equilibrium of the system through iterations (Wardrop & Whitehead, 1952). A stochastic approach often relies on random utility models (Ben-Akiva & Lerman, 1985) in which behavioural uncertainty is considered.

More information concerning traffic evacuation models for wildland-urban interface scenarios can be found in (Intini et al., 2019), where 22 traffic models are identified and their use is analysed for the specific case of wildland-urban interface fire evacuation. Also in this case, models may adopt different types of approaches from the perspective of how individual vehicles are represented (e.g., using a macroscopic, microscopic or mesoscopic approach). In addition, models may be able to represent certain variables and factors in an implicit or explicit way. Depending on data availability, complexity, and area and population size of the scenarios, the users should select a model which is able to capture the specific features which relate to evacuation in the wildland-urban interface in touristic areas. In particular, the presence of people with widely different characteristics (locals vs tourists) should be considered to a great extent.

7. Coupled evacuation models

To date, the most recent literature in the domain of wildland-urban interface fire evacuation relates to the coupled representation of different modelling layers. This includes the coupled representation of pedestrian (response and movement) and traffic evacuation. Based on the work by (Ronchi et al., 2017), it is possible to consider the timelines related to different modelling layers. An example is presented in Figure 2.

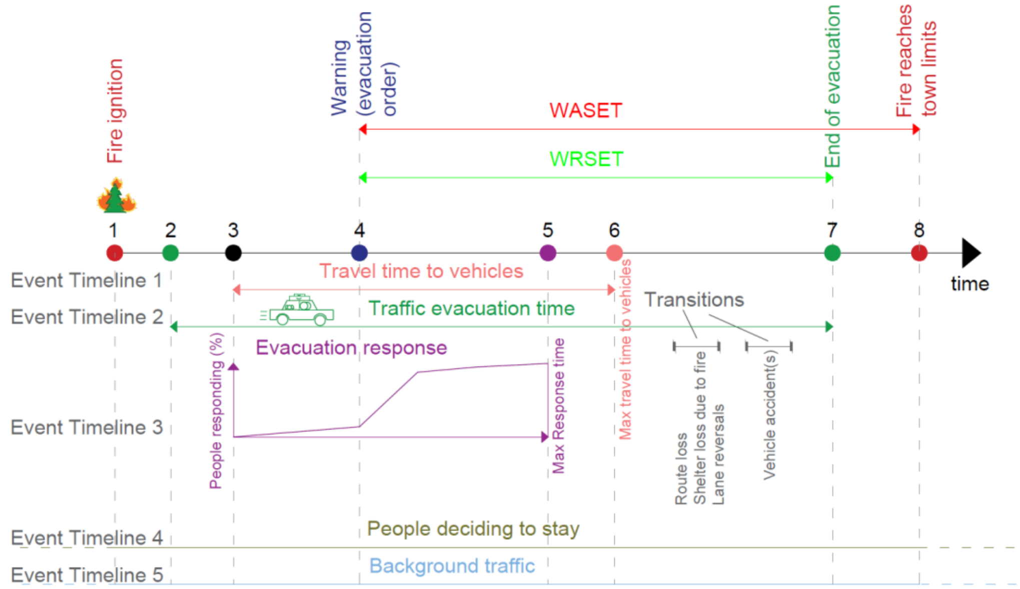

Figure 2. Schematic representation of an example of timelines related to different modelling layers in a wildland-urban interface fire scenario, from (Ronchi et al., 2017).

Coupled models attempt to represent not only the individual modes of transport, but also both the interaction between different transport modes (e.g., a pedestrian reaching a private vehicle to evacuate on the road network) as well as the interactions with the wildfire threat. This implies that model users should also be familiar with wildfire modelling, as well as be able to collect the typical inputs required by such models (e.g., topography, fuel or weather-related).

The required data exchange in a wildland-urban interface fire evacuation scenario in touristic areas include how the wildfire affects pedestrian and traffic movement, transportation mode availability, the conditions of the evacuation routes, and access to communication (Ronchi et al., 2017). The wildfire threat may impact both the availability of destinations and routes during evacuation as well as human response (e.g., the smoke or the fire front being a trigger for evacuation (Cova et al., 2005; Mitchell et al., 2023)) and the ability of evacuees to reach a safe place. A remarkable example in this domain is the representation of the impact of smoke on evacuation as it can severely slow down the evacuation process (Intini et al., 2022; Wetterberg et al., 2021). This issue could be exacerbated further in touristic areas given the fact that route familiarity plays an important role in speed choice (Colonna et al., 2016) and the presence of smoke may make the environment even less familiar.

The availability of information (environmental or social cues) has a strong importance in the representation of evacuation in touristic areas at the wildland-urban interface. In fact, evacuation choices may be different in relation to the type of population under consideration (tourists vs locals). In this context, the direct representation of visual cues (e.g., smoke or fire-front) allow an explicit simulation of how the evolution of the fire front can impact decision making.

The traffic modelling component may also affect the evolution of the fire threat (since traffic congestion may affect land fire-fighting) but to date this aspect is not addressed in existing models (Ronchi et al., 2019).

The scales under consideration would also play an important role in the coupled representation of evacuation and the wildfire threat. In fact, spatial and temporal scales are known to have strong implications on computational requirements (Ronchi et al., 2019), thus affecting the choice of the modelling approach to be used. While simplified models refer to empirical modelling approaches, refined models may rely on physics-based or agent-based representation. For example, a physical representation of the fire evolution may be extremely computationally expensive, meaning that a consistent level of granularity in the modelling should be a starting point towards a reasonable representation of a wildfire evacuation scenario.

Examples of coupled models can be found in the literature (Beloglazov et al., 2016; Cova et al., 2005, 2005; Dennison et al., 2007; Filippidis et al., 2020; Grajdura et al., 2022; Mitchell et al., 2023; Ronchi & Gwynne, 2019; Wahlqvist et al., 2021). In general terms, those tools are to some extent able to represent one or more of the above-mentioned aspects related to the coupling the wildfire threat with the evacuation process. The user should evaluate their individual features considering the critical aspects related to wildfire evacuation in touristic areas, such as the availability of information to tourists and how this is related to the actual evolution of the fire threat.

8. Examples of scenarios of interest

This section provides two examples of possible scenarios that may be considered representative to investigate the capabilities of different models in addressing fire scenarios in the wildland-urban interface where touristic infrastructures are present. Those scenarios are deliberately different and deal with different evacuation scales.

The first suggested scenario is a camping scenario, which presents a set of interesting complexities from the modelling perspective given the fact that the layout of obstructions in this type of scenarios is not necessarily fixed. Considering as main goal of the analysis the estimation of the time required to evacuate the camping. This scenario can be represented with a pedestrian evacuation model, therefore key inputs to be included are:

- Possible geometric configuration(s) of the camping site (also in relation to occupancy level) and associated movement flow constraints;
- Information concerning the topography and type of terrain present in the camping site;
- Occupant load;
- Initial occupant location: How people are distributed in the different areas of the domain at the start of the simulation.
- Physical occupant characteristics (movement abilities, anthropometric information);
- Definition of occupant behavioural scenarios, analysing behavioural archetypes present in the site and subsequent probability of behaviours (e.g., pre-evacuation response, route choice, group behaviour, need of assistance for people with functional limitations or children).

Given the complexity of the geometry and the scope of the analysis (focussed on evacuation on foot), a microscopic pedestrian evacuation simulator can be used (e.g. Pathfinder (Thunderhead Engineering, 2020)). Pathfinder is an agent-based microscopic model that represent people movement adopting 2D navigation meshes connected with vertical elements (e.g., ramps that can be used to represent a given slope). Unimpeded walking speeds can also be customised based on speed factors which may be dependent on the type of terrain under consideration. Hence, agents can change their desired speed depending on the area they are walking in. A locally quickest path is adopted to reach the final destinations (Thornton et al., 2014). Movement is modelled through either a steering model (Reynolds, 1999) or a hydraulic macroscopic modelling approach (Gwynne & Rosenbaum, 2016). Model outputs include specific flow (flowrate of pedestrians per unit width at destination), total evacuation time, queuing times, occupant-evacuation time curves (those include evacuation time of each individual), occupant density levels achieved during an evacuation and level of service.

Within the WUITIPS project, an example of camping site that is currently being considered for simulation is the Camping l'ombra, in Llançà which includes 200 plots (available for caravan/tent or bugalows), with an expected population in the order of hundreds of people.

The second suggested scenario is the evacuation of a WUI touristic community. In this scenario a traffic evacuation simulation will be performed. The goal of this scenario is to estimate the time needed for the population to perform an evacuation via private vehicles (e.g., cars) on the road network and should include the time needed to access their vehicles.

The key needed inputs for this scenario are:

- Location and size of the region under consideration
- Definition of the population in the area
- A landscape file (e.g. in .lcp format) including elevation, slope, aspect, canopy cover and fuel raster layers (in case of combined fire simulation). If not directly available, slope and aspect layers can be calculated from the elevation layers using GIS. Fuel models can be obtained by the European Forest Fire Information System (EFFIS) or a local survey authority
- Road network information through OpenStreetMap data e.g., in .osm.pbf format.
- A routing network database calculated from the OSM data file should be defined based on expected destinations
- Estimated number of private vehicles (e.g. cars) in the area

Outputs will include the time to reach destinations, the number of people evacuating or staying in the area, the number of vehicles in the area over time and the evacuation time curves.

Given the scenario focussing on traffic evacuation, this scenario can be simulated either with a "pure" traffic model e.g., SUMO (Behrisch et al., 2011) or with a coupled evacuation model including the traffic component, e.g. WUI-NITY (Ronchi et al., 2020). SUMO "Simulation of Urban Mobility" is an open source microscopic and continuous traffic model. It is designed to handle large traffic scenarios in normal circulation conditions, but it has been already used for evacuation scenarios (Filippidis et al., 2020; Flötteröd & Erdmann, 2016). WUI-NITY is freely available platform for simulating three modelling layers (fire spread, human response/movement and traffic evacuation) related to wildland-urban interface fire evacuation (Ronchi et al., 2019, 2020; Wahlqvist et al., 2021).

Within the WUITIPS project, an example of a WUI touristic community is "Cap de Ras" in Llançà, where the order of magnitude of the population is up to thousands of people.

9. Discussion

This section analyses the findings of the literature review performed taking into consideration the objectives of this work.

Objective 1) To identify different types of models in relation to the evacuation mode under consideration.

The review identified different types of models that can be used for the representation of evacuation in the wildland-urban interface in touristic areas. The main transportation modes which are taken into consideration are evacuation on foot (via pedestrian modelling) and evacuation via private vehicles (via traffic modelling). Transportation via public vehicles is currently not addressed in most models. While the number of pedestrian and traffic evacuation models is relatively large, most of those are not explicitly designed for wildland-urban interface scenarios, and none of them is specifically designed for the representation of human behaviour in touristic areas. Coupled models allow the representation of multi-modal evacuation scenarios and in some instances represent the impact that the wildfire threat has on evacuation (e.g., through the impact of smoke or fire spread on evacuation (Intini et al., 2022; Wahlqvist et al., 2021) or when the wildfire acts as trigger for the evacuation (Cova et al., 2005; Dennison et al., 2007; Mitchell et al., 2023)). A dedicated study has also been identified which addresses specifically the representation of evacuation via unconventional means (Tyler, 2021). Regarding the latter, the development of tools for this purpose is still at an initial stage, and to date, the simulation of evacuation via sea or air would require a dedicated effort by the user to overcome the fact that the existing models are not originally designed for such scenarios. For this reason, the use of evacuation models for such unconventional means would require further research efforts in their development. Evacuation models can also be classified in relation to the level of granularity they adopt for the representation of evacuation movement and behaviour. The two main modelling approaches in use include 1) microscopic modelling (in which each person or vehicle is simulated as an individual entity) and 2) macroscopic modelling (in which groups of people or vehicles are treated as aggregates). Intermediate approaches such as mesoscopic modelling (Burghout, 2005) are currently not widely used in this domain. Space representation can also be performed differently, considering that the area under consideration can be represented either with network approaches or as a continuous space (Ronchi & Nilsson, 2016) or a combination of those approaches (Chooramun, 2011).

Objective 2) to identify the key modelling inputs required for the representation of the evacuation of people in the wildland-urban interface in touristic areas.

Depending on the transportation mode under consideration and the modelling approach in use (e.g., microscopic vs macroscopic), evacuation models may require a different set of inputs for the representation of the evacuation of people in touristic areas. General inputs required by models include the topography and layout of the area (e.g., elevation, slope, aspect, etc.) including information concerning the location of households, evacuation routes (e.g., road network or pedestrian paths) and key landmarks (e.g. a lake, river or critical infrastructures such as hospitals), and inputs concerning the number of people in the threatened area. The representation of the decision-making process during evacuation also requires information about the physical and psychological characteristics of evacuees (Katzilieris et al., 2022; E. Kuligowski, 2020) and their access to transportation modes (e.g. access to a private vehicle or vicinity to public evacuation transportation means). In the case of touristic areas, it is important to be able to simulate the heterogeneity in behavioural responses between locals and tourists. This should be considered at different scales (individual or in groups) depending on the modelling approach under consideration (microscopic or macroscopic). In coupled models, the representation of the impact of wildfires on evacuation would require all typical inputs of wildfire models which would vary in their number and level of detail in relation to the granularity of the wildfire modelling approach in use (e.g., physical models, semi-empirical or empirical models). Along with this information, inputs regarding wind, fuel moisture content and weather conditions would be required as well prior the simulation of the wildfire modelling layer and how it will impact evacuation. Information concerning the destinations of evacuees (shelters or areas at the edges of the space under consideration which could be considered safe locations) should also be identified. In case of microscopic modelling, many more detailed inputs may be required for the representation of human behaviour and movement. These inputs depend on the level of model granularity and the transportation mode(s) being represented.

Objective 3) To provide an overview of the capabilities of the main available evacuation models to simulate evacuation with different transportation modes.

The current capabilities of evacuation models widely change in relation to the modelling approach in use. In general terms, microscopic evacuation models allow for a detailed representation of the sequence of actions that people may perform during an evacuation. Depending on their level of flexibility and range of inputs that they include, they would allow for implicit or explicit representation of a simpler or more complex behaviours.

Regarding pedestrian models, they are generally designed for the representation of evacuation behaviour and movement at household level (also in case of multiple connected or disconnected buildings) or in outdoor environments. Macroscopic pedestrian models (such as hydraulic calculations (Gwynne & Rosenbaum, 2016; Predtechenskii & Milinskii, 1978)) allow for a quicker estimation of evacuation times, while making use of several simplifications and assumptions.

Regarding traffic models, they can also include varying level of refinement based on their approach in representing movement at individual or aggregate level. Also in this case, a refined representation of individuals allows for a more detailed characterization of different populations, a very important aspect when representing the behaviour of tourists in relation to locals.

Coupled models may allow to consider explicitly the interaction between different transportation modes and the interaction with the wildfire threat. The explicit representation of the threat may be an important aspect to consider when modelling the behaviour of tourists, given the fact that the direct cues of the threat may be an important source of information for them. This is associated with the fact that they may not have access to the same amount and type of information that locals have, or interpret the information in the same way.

Objective 4) to discuss the relationship between the granularity of the model (e.g., microscopic vs macroscopic), the uncertainty in the inputs and the scale of the scenario under consideration.

While evacuation model developers generally do not explicitly state a limit in the area size they are designed for, there may be limitations related to the number of people or vehicles they are able to accommodate without incurring in computational constraints. In general terms, the most advanced evacuation models are generally designed to handle scenarios up to hundreds of thousands of people (with pedestrian models generally used up to one hundreds of thousands and traffic models designed for several hundreds of thousands of vehicles). Nevertheless, users should take into consideration that for such large scenarios computational time may become an issue (depending also on the application use of such models, e.g., evacuation planning vs real-time emergency managements). It should also be noted that probabilistic evacuation models generally make use of pseudo-random sampling from distributions, meaning that it can be necessary to simulate the same scenario multiple times to assess the convergence of results (Ronchi, Reneke, et al., 2014; Smedberg et al., 2021). This implies that computational considerations should be made while choosing the modelling approach for simulating a given scenario with a pedestrian evacuation model. This relates both to the representation of the population (e.g., a microscopic approach would generally require higher computation compared to macroscopic approach) as well as space representation (a network approach is generally faster than modelling a continuous space)

The spatial scale of traffic models is generally larger than the case of pedestrian models, meaning that their use should be considered suitable also for very large communities and areas, while pedestrian models are more usable at building level or in relatively small areas (e.g., touristic infrastructures such as camping sites).

Objective 5) to provide recommendations for future model improvements in relation to their application in the context of wildland-urban interface in touristic areas.

Future model developments should include a refined impact of topography on evacuation and a more detailed characterization of population characteristics. Pedestrian evacuation simulators generally make use of homogenous 2D navigation meshes connected with vertical elements (e.g., ramps). Such approach is not suitable for outdoor wildfire scenarios as the camping case study discussed here, where the slope and type of terrain can affect movement speeds. In the context of touristic areas, an important aspect to be considered is how model would explicitly or implicitly represent the impact of different demographics and behaviour-related variables on evacuation decisions and actions. The most refined models (e.g., microscopic models) are currently flexible enough to represent several key variables related to tourists (e.g., impact of demographics, experience, etc.), but they require a set of detailed inputs in order to be credibly calibrated. Here, the availability of human behaviour data regarding the evacuation of different population types is paramount for the future developments in the modelling domain. Existing models which explicitly consider aspects like risk perception and social influence (Lovreglio et al., 2016; Lovreglio, Kuligowski, et al., 2020) indeed require inputs which are generally not available to model users. When this is the case, the use of a probabilistic approach is recommended, as it allows to balance the uncertainty associated with the inputs.

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