Evacuation modelling for community resilience: An Australian perspective

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ABSTRACT

Communities worldwide are increasingly facing severe impacts from natural hazards like wildfires, floods, and cyclones. Where a life-threatening hazard is imminent, and moving people is a safe option, large-scale evacuations of communities are often undertaken by authorities. In Australia, where evacuation is a recommendation to individuals and households, and not an enforceable order, community safety requires a collaborative approach: where communities take ownership of the risk and responsibility for their actions, and work closely with emergency management agencies for planning, preparedness, readiness, and response efforts. In this context, drawing examples from existing works, we present requirements for evacuation modelling from the perspectives of different end-users (the at-risk individuals and households, the town planner and developer, the risk analyst, the incident controller and response crew). We argue that this technology is useful, beyond its obvious use in planning and decision support, in building shared understanding among all stakeholders for improving community safety.

Keywords

Wildfires, Evacuation, Modelling, Simulation, Resilience

INTRODUCTION

With the increasing frequency and severity of extreme weather-induced natural hazards worldwide, large-scale evacuations of communities out of harm's way are becoming increasingly regular. Between 2017-19, in excess of one million people were evacuated from wildfires in California, USA (Wong & Broader, 2020). In 2023 alone, an estimated 200,000 people were evacuated during Canada's unprecedented fire season (Beverley, 2023), more than the combined total for the 1979-2007 period (Beverly & Bothwell, 2011). Hundreds of *bushfires*, the analogous term for wildfires in Australia, devastate vast landscapes in Australia every year, and can bring with them disastrous consequences for communities (Binskin et al., 2020; Teague et al., 2010). Against this backdrop, understanding evacuation-related human behaviour to inform choices in future events is becoming vital for all involved, from evacuating communities to emergency management agencies tasked with their timely egress to safety.

Recent years have seen significant advances in computer-based simulation technology for modelling large-scale evacuations, offering many benefits to planning and preparedness for future events. In the simplest use case, this technology can help improve understanding of traffic and timing when moving populations en masse (Goto et al., 2012; Wahlqvist et al., 2021). Combined with hazard progression modelling, it can allow evacuation policies to be stress tested under "what-if" scenarios (Goto et al., 2012; Wahlqvist et al., 2021), inform training of emergency personnel (Ronchi et al., 2017), improve community education and information (Goto et al., 2012), and bring a shared understanding of roles and responsibilities between authorities and communities (Chen et al., 2021). The ability to model complex human behaviour at a granular level, even down to every individual in a community, using techniques like agent-based modelling (Goto et al., 2012; Wahlqvist et al., 2021), are nothing short of impressive (Goto et al., 2012; Wahlqvist et al., 2021), and work to demonstrate that the technology is up to the challenge and abounds in academia (Ronchi et al., 2017).

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Table 1. Evacuation modelling use cases.

	Planning	**Preparedness**	**Readiness**	**Response**
Decision timeline	Years ahead	Season ahead	Week ahead	Day of incident
Use cases	Integrated land use and transport planning, Risk reduction planning, Emergency planning for townships, Community education	Seasonal risk assessment and reduction, Adapting emergency plans, Preparedness exercises, Community information, Special events (e.g., festivals)	Emergency resources allocation, Community messaging, Special events arrangements	Evacuation options and messaging
Example actions	Constructing and upgrading community refuges, Identifying and upgrading roads and bridges for safe egress, Establishing standard operating procedures, roles and responsibilities	Pre-season incident management training, Community awareness programs, Adapting township emergency plans, informing traffic management arrangements	Community information, Leave early messaging, Event management, traffic management, emergency resources positioning and readiness	Evaluating if/when/how evacuations are conducted, Timing of leave or shelter messaging, Providing directions for safe egress, Placement of traffic management resources
End users	Agencies responsible for risk reduction, town and infrastructure planning, emergency management, Local / State / Federal governments, Building & construction industry	Emergency management agencies, Local / State governments, Township emergency planning committees, Community groups, Local residents, Event planners, Tourism agencies	Emergency management agencies, Community groups, Local residents, Event planners, Tourism agencies	Emergency management agencies

Despite improvements in computing software and hardware that have made evacuation simulation technology accessible today, these models continue to live largely in the domain of researchers and not practitioners. This sits in stark contrast to models of natural hazards, such as bushfires (Bally, 2023; Faggian et al., 2017), that are widely used in emergency management at all levels of operations and across all timescales from planning to response. Why so? In this paper we argue that the uptake of evacuation models is hindered today not as much due to technological challenges as it is due to social ones. What is lacking often is a clear understanding of the audience and a solution adapted for its needs. *Evacuation modelling for whom?* We argue for the need of a socio-technical approach: one that optimises not just the technological solution, but equally, and jointly, its use in society. In this setting there is no linear technology transfer from producer to consumer, rather an iterative process of co-production, co-learning, and product evolution.

While it is evident that evacuation related decisions must be made at the time of a bushfire, the timeline for evacuation decisions begins several years prior to the event. For many jurisdictions, emergency management arrangements relate to the timing of decisions before, during and after an emergency, and apply to the four broadly defined phases of Prevention, Preparedness, Response, and Recovery (PPRR) (Community Outcomes and Recovery Subcommittee (CORS), 2022). In this framing, evacuation decisions fall under the first three phases. When assessing how evacuation modelling can help inform decisions, it is useful to consider *when* decisions have to be made, *what* decisions can benefit from the outputs of the modelling, and *who* is making the decisions. Table 1 shows the timeline before and during a bushfire split into four phases: Planning that begins several years before the event and where related actions can take years to implement, Preparedness where actions align with the cycle of seasons every year, Readiness defined by actions in the days leading to an event, and Response relating to actions during the event. In this paper, and with a focus on Australia, we argue the need for a deeper appreciation of these use cases and end users and their requirements, when building evacuation modelling and simulation capability.

Consideration of community evacuations is a relatively new concern in Australia. As recently as the disastrous 2009 Black Saturday bushfires during which 173 lives were lost, Australia had no standing policy around evacuations. The subsequent 2009 Victorian Bushfires Royal Commission (Binskin et al., 2020) made 67 recommendations, of

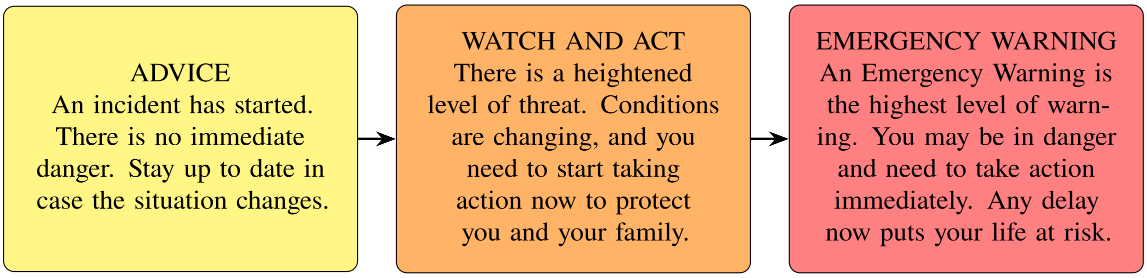

Figure 1. Warning levels under the new Australian Warning System.

which Recommendation 1, 3, and 5, sought a comprehensive approach to evacuations. A decade later, following the devastation of the Black Summer bushfires of 2019-20 that resulted in 34 direct casualties, and an estimated additional 417 deaths from bushfire smoke exposure (Borchers Arriagada et al., 2020), the Royal Commission into National Natural Disaster Arrangements (Binskin et al., 2020) expanded on the need for a national approach to evacuation planning and shelters. The evacuation context in Australia is one of vast landscapes prone to natural hazards and large numbers of relatively small and dispersed populations at their interface. During hazard events, such as bushfires that burn hundreds of thousands of hectares every year in Australia, limited resources exist within emergency services to attend to everyone in need. For the first few critical hours of an emergency until help arrives, it is the collective actions of impacted communities that have the biggest impact on lives saved.

Evacuations in Australia are additionally not mandatory. For this reason, improving community preparedness to take preventative action has been a focus of media campaigns from emergency agencies. Between 2009 and 2020, the nationally agreed Prepare Act Survive campaign saw the percentage of people who were prepared with a plan of action improve from 30 percent to 80 percent (NSW Rural Fire Service, 2023). However, residents who intend to leave have little in the way of knowing what conditions will be like once they become mobile. Evacuation simulation tools with map-based visualisations of expected behaviours and estimated traffic can show how decisions and actions of residents and emergency services translate to traffic and congestion on roads, and help improve individuals' understanding and planning.

The remainder of this paper is structured as follows. In the next section we describe important use cases and end users of evacuation modelling, focusing on Australia, then set out what we believe are key requirements for evacuation modelling capability from an applied perspective towards building understanding and improving community resilience. The subsequent section then covers current state-of-the-art in evacuation modelling capability in this context. Finally, in the discussion we reflect on what is required to get evacuation modelling tools to a level where they can confidently be used across bushfire planning, readiness, and response in Australia.

EVACUATION MODELLING FOR WHOM?

In this section we discuss evacuation modelling from an end user perspective across the decision timeline, in an attempt to highlight the importance of accounting for these perspectives when designing and implementing evacuation modelling technology.

The At-Risk Individual

The new Australian Warning System applies a nationally consistent approach to information and call to action for hazards like bushfire, flood, storm, cyclone, extreme heat and severe weather [1], and was established following recommendations from the Royal Commission into National Natural Disaster Arrangements (Binskin et al., 2020). Under this scheme, three warning levels communicate increasing risk to communities, as shown in Figure 1. Each warning level is associated with a set of action statements that give the community clear advice about what to do. Evacuation-related actions can accompany a Watch and Act warning with action calls including "Prepare to evacuate", or "Evacuate now," while for the more severe Emergency Warning the wording can include "Evacuate immediately" and "Seek shelter now".

An individual's awareness of the situation is a function of many factors, emergency warnings being one. Other important sources that contribute to awareness include visual cues such as the sight of smoke, embers, flames, and neighbours leaving, the sound of emergency vehicles and aircraft, communications from family and friends, and broadcasts through public information channels (Whittaker, 2019). Acknowledgement of the situation at a level that

[1]https://www.australianwarningsystem.com.au

Figure 2. Examples of the use of evacuation modelling for community information and education as shared by the Commonwealth Scientific and Industrial Research Organisation (CSIRO Evacuation Modelling Group, 2023).

warrants deliberation happens over time and via reinforcement of information from different sources. Individuals vary in their perceptions of risk which influences if and when they take action (McLennan et al., 2019).

Whether situation-aware individuals choose to evacuate varies significantly still. Extensive work by Strahan et al. on self-evacuation archetypes in Australian bushfires (K. Strahan et al., 2018; K. W. Strahan et al., 2019) shows that behaviours of resident individuals can be classified into one of seven distinct groups. A Threat Denier pays little heed to warnings because of the belief that their personal safety is not threatened by the bushfire, making evacuation unnecessary. Similarly, an Experienced Independent is also committed to remaining at home but for the reason that they are experienced and believe they are well prepared to fight the fire. In contrast, a Worried Worried Waverer hesitate between leaving and staying as they are not confident in their ability to defend their property despite prior training. A Community Guided person is constantly seeking information to stay informed, and values official advice when deciding to evacuate. A Responsibility Denier on the other hand is a committed evacuator who expects to be told what action to take when, effectively taking no responsibility for their own safety. Whereas, a Dependent Evacuator is incapable of taking protective action and relies on others for their safe evacuation. Finally, a Considered Evacuator is strongly committed to evacuate as soon as they become aware of the threat. While these self-evacuation archetypes give useful insights into behaviours of residents, they currently do not extend to households or seasonal visitors.

Even where a decision to leave or shelter nearby is made, there is still further variation in how decisions translate to trips. First, the distribution of departure times is skewed with a large number of people typically leaving sooner than the mean departure time, and a relatively smaller proportion leaving quite a long time after. Then a significant proportion of the population may undertake *intermediate* trips, which are trips to destinations other than the final evacuation destination, such as trips to pick up dependents from school or pets from homes. Finally, any trip, including the one to the evacuation destination may be disrupted by a change in the situation such as fire ahead, fallen tree over road, an accident, or redirection from traffic management authorities. In such situations, people may look for alternative routes to their destination, or failing that, look for alternative destinations. Lack of data on evacuation related behaviour and mobility are open challenges for evacuation modelling (Kuligowski, 2021).

Evacuation modelling capability should allow for heterogeneity and variation in behaviour expected during a real event towards more realistic estimates of egress times (Bulumulla et al., 2017; Robertson et al., 2021; Singh et al., 2021) and importantly of risk to communities. Simulations of evacuation can be extremely beneficial for community information, awareness, engagement, preparedness, and ultimately resilience to bushfire threat. Examples of this use case in Australia are seen in the evacuation modelling work being undertaken at the Commonwealth Scientific and Industrial Research Organisation (CSIRO). These include the use of evacuation modelling for information and education at community events (Atkin, 2023; Gamage, 2022, 2023), and for improving resilience through direct community engagement in the co-production of evacuation scenarios with support from the emergency services (Dennis, 2022) (see Figure 2).

The Town Planner and Builder

A recent high-profile case in Western Australia demonstrates the relevance of evacuation modelling in assessing the suitability of proposed new housing developments in high bushfire risk areas. Perth Hills in Western Australia suffered significant bushfires in 2011 (71 homes destroyed) (Keelty, 2011) and 2014 (48 homes destroyed) (Smith et al., 2015). Recently, concerns over a planning proposal for a township to accommodate approximately 1000 new dwellings there has seen significant government scrutiny (Government of Western Australia, 2023) and public protest (Perth Hills Action Group, 2023). The proponent developer submitted updated plans to address concerns, including a report on evacuation modelling for the proposed township. After final review, and hearing from public and experts, the planning committee recommended to the planning commission that the proposal be refused. In

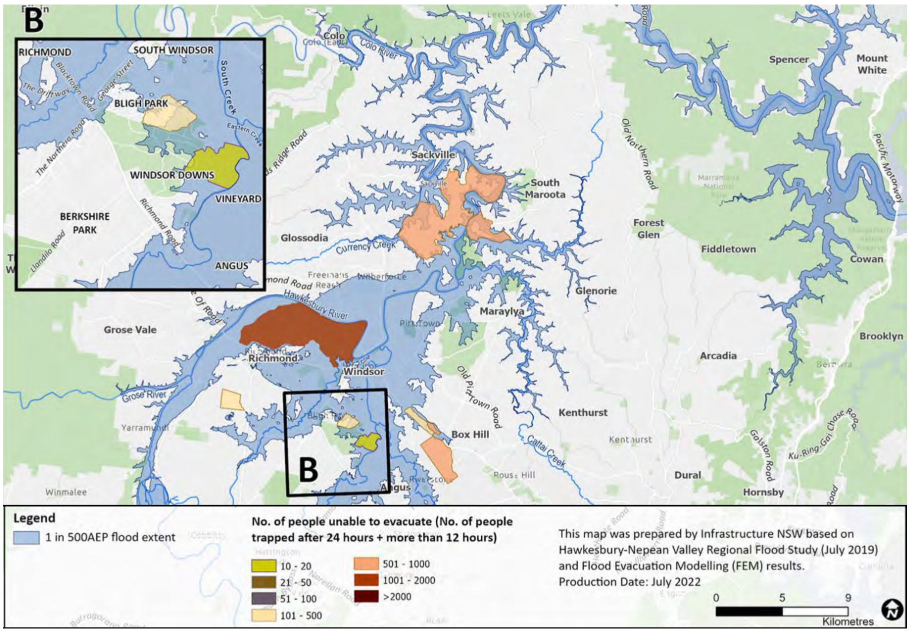

Figure 3. Extract of Figure 4.6 from NSW Government (2023) showing an estimated 6-fold increase in the number of people unable to evacuate in a 1 in 500 chance per year flood, under a medium mid-century climate change scenario with additional committed housing developments up to 2041, compared to the 2018 base case.

making its recommendation, the committee noted that the plan "does not demonstrate that the threat of bushfire risk to people, property and infrastructure can be appropriately mitigated [. . .] because: a. the technical information submitted in support [. . .], including traffic, evacuation and bushfire analysis and modelling, does not include adequate or accurate details to demonstrate that the risk of impacts from a bushfire, including safe evacuation in a bushfire emergency, is acceptable;" The case is significant because evacuation modelling played an essential role in the assessment of risk to a proposed future community from bushfires. It highlights the requirement for evacuation modelling to be "adequate and accurate" to be considered suitable for decision making. It emphasises the requirement for a tight integration between the fire progression modelling and evacuation modelling. Importantly, it demonstrates the demand for this capability for town planning in bushfire-prone areas.

An example of detailed evacuation modelling in Australia that was considered adequate and accurate for planning purposes, in this case by the State of New South Wales, including Infrastructure NSW, Transport for NSW, the NSW State Emergency Service, and the NSW Department of Planning and Environment, is the Flood Evacuation Model (FEM) developed by the CSIRO in collaboration with industry and academic partners (NSW Government, 2023). FEM was built to inform flood risk management planning in the Hawkesbury-Nepean river valley near Sydney, for use by government agencies and local councils responsible for integrated land use, transport and emergency planning in the area. FEM simulates the NSW State Emergency Service evacuation arrangements in current and future planned development scenarios (2018, 2026, and 2041) across a suite of representative flood events (from a 1-in-50 to 1-in-5000 chance per year). Through thorough analysis of results from a large ensemble of simulation runs, FEM provides an understanding of road network performance and capacity constraints for estimated evacuating traffic; assesses risk to life from saturated capacities and congested traffic flows against impending flooding; and estimates risk reduction from potential road upgrades (see Figure 3).

The Risk Analyst

Fire progression models like Phoenix, Aurora/Australis, and Spark are used within Australian emergency services (Faggian et al., 2017) at various levels of operation and time scales (see Table 1) from readiness to incident response. Personnel trained in the role of a fire behaviour analyst (FBAN) are responsible for collecting weather and fuel load information, simulating and studying fire progression under known and forecast conditions, and providing predictive insights to positioned or operational crews, towards reducing risk to lives, livelihoods, properties, and infrastructure. On days when fire danger is rated High, Extreme, or Catastrophic, an FBAN may run several fire progression simulations at the start of the day, prepare a summary on likely progression of select fires that had the potential to cause significant damage to communities and assets were they to ignite, and distribute the predictive insights to relevant teams. In ongoing fires, FBANs are installed in Incident management Teams and operate in

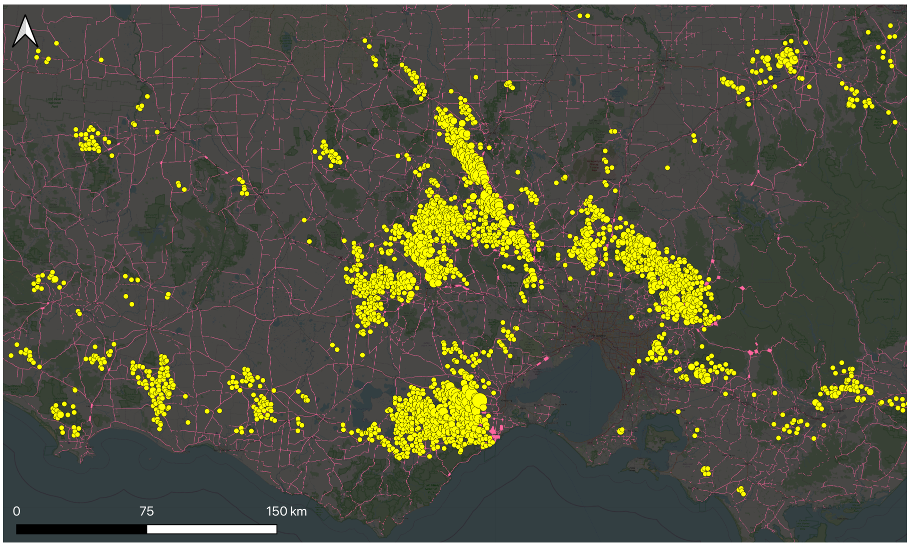

Figure 4. Example SAFER outputs showing evacuation hotspots in Victoria, Australia, as reported by Singh et al. (2023). Larger fire ignitions (yellow) are more problematic, while thicker road segments (pink) are more critical, for evacuating traffic.

Incident Control Centres at local, regional and state levels. Outside of Australia, the FBAN role is also employed in the USA. It is likely, under current emergency management arrangements, that the responsibility of running evacuation scenarios using outputs of fire progression models as inputs would fall initially on the FBAN. This highlights several important requirements for evacuation models: of timely, trusted, easily interpreted, explainable, and unambiguous outputs for accountable decision-making downstream.

Strategic long-term fire risk assessment is performed for large jurisdictions across a set of fire ignitions under different weather and wind conditions. Predictive Services within the Department of Energy, Environment, and Climate Action in Victoria, Australia, used "millions of fire simulations across the state to identify high risk areas, test different fire management scenarios and quantify risk reduction from delivered treatments" (Melero Blanca & Brien, 2023). Similarly, the Western Australian Department of Fire and Emergency Services used six million fire simulations to assess power network related fire risk from ignitions sparked at any power pole in the state's southwest (Parker & Allen, 2019). The CSIRO reported on the SAFER model, that consumes these very large sets of fire simulations to compute aggregate evacuation risk "hotspots" (see Figure 4 for Australian states (Singh et al., 2023). Noting the sheer size of the task, authors emphasise additional requirements for evacuation modelling capability in this context as: "The design goals for SAFER are (i) *scale*: supporting risk assessment for areas as large as Australian states and territories, and across hundreds of thousands of simulated fire ignitions, (ii) *speed*: computing state-wide evacuation risk metrics within hours, and (iii) *automation*: producing outputs automatically with no manual steps."

The Incident Controller and Response Crew

During a rapid-onset bushfire event, the Incident Management Team consisting of personnel representing all relevant emergency agencies is immediately activated in Australia, with explicit processes and protocols for emergency management and escalation. Within this team, it is the role of the Incident Controller (IC) to make the decision to evacuate or not, often under time pressure and with limited situation awareness. This is a decision that comes with enormous responsibility because if made incorrectly it can put people directly in harm's way.

Evacuation modelling capability that could provide fast and valuable insights into possible consequences for the community at risk, that the IC could take into account when considering the options, would be beneficial to the IMT as an additional source of assessment of the situation. However, for this to work, the technology must be trusted by the IC, allow exploration of emergency response scenarios the IC is considering in the situation, provide information on worst and likely consequences in forms that can be quickly understood by the IC, answer questions according to an explicit decision workflow the IC must follow, and highlight decision aspects that community safety outcomes are most sensitive to and may require careful attention. The reality is that the IC makes the decision to evacuate or not, for every bushfire that may interact with communities, evacuation models at hand or not. However, were such capability available, it would provide a valuable data-driven perspective to inform decisions. While this

Figure 5. Evacuation modelling use in Incident Management Team training as reported by Singh et al. (2022).

example is specific to one region and hazard, comparable emergency decision arrangements exist in many parts of the world and in the end a human is in charge of making the important decision on evacuation. The evacuation modelling capability must fundamentally cater to this user's requirements.

Singh et al. (2022) reported on the use of bushfire evacuation modelling in a multi-agency joint Incident Management Team training exercise organised by the Department of Environment, Land, Water and Planning at the dedicated Geelong Incident Control Centre in Victoria, in preparation for the 2021-22 bushfire season. During the live real-time training, evacuation modelling against the hypothetical fire was presented to the IMT in the form of analysis from several "what-if" evacuation scenarios of emergency response (see Figure 5). These scenarios included varying of timing and severity of warnings, partial or full implementation of manned traffic management points at intersections as per the local traffic management plan for emergencies, and combinations thereof. Outputs included map-based visualisations, videos of simulated evacuations against the fire progression, summaries of estimated consequences from each, and recommendations for the IC. Post-event reflection showed that evacuation modelling was a useful source of additional information for the IC who consulted the modelling on several occasions through the day. Authors noted that videos of evacuating vehicles were referenced by participants more than zone-based visualisations of evacuation metrics, hinting at the need for outputs that are fit-for-purpose. Post-event debriefing also identified areas of improvements including the ability to re-run scenarios in real-time to estimate reduction in risk to lives following IMT decisions.

EVACUATION MODELLING REQUIREMENTS FROM END USER PERSPECTIVES

We now return to an earlier point made in the Introduction that the adoption of evacuation models in disaster risk management requires addressing not just scientific or technological challenges, but societal barriers as well. In other words, the development of appropriate technological solutions must be guided by clearly articulated societal needs. Related to this point is the fact that, as is apparent from the previous section, different end users may have very different needs, and therefore it is imperative that modellers resist the temptation of a one-size-fit-all approach. Rather, each use case may call for a different approach, not just in the modelling techniques used, but also in the design of the corresponding software solution. At this point, an argument may be made that the term end users should be interpreted broadly, that is any individual or organization utilizing the outputs of a model in their decision making process. This does not necessarily imply that end users are responsible for executing the simulation scenarios themselves, but rather that the outputs of such scenarios should be made accessible to them.

As highlighted in the Introduction, the design process is inherently iterative, involving developers, researchers and end users. The objective during this phase should be to clarify the intended use of the model as much as possible, in order to create a solution that is fit for purpose. Relevant questions should include for example: What questions does the model need to be able to answer? What input data is required, and is it readily available? How fast does the model need to run? What kind of outputs does it need to produce, and in what form? Who is responsible for running the models and producing results? If there is technology transfer, how is the risk of mishandling complex scientific software managed?

Irrespective of the specific use case considered, generally speaking a model of evacuation will need to address broad categories of key requirements, including:

- *Ability to set up multiple simulations scenarios*. This requirement includes the need for the model to easily ingest input data with minimal human intervention to miminimize time-consuming tasks, human errors, and enhance provenance processes and scenario reproducibility. An additional challenge specific to the use of these models in a response context is the ability to access live data, which may be challenging due to privacy reasons.
- *Capture of Important Evacuation Scenario Features*. The model should capture crucial features of the evacuation scenario under consideration. For instance, human behaviour modelling is critical for regional-scale evacuations but may be mostly irrelevant when identifying potential hotspots for evacuation risk at a larger scale (e.g. state-wide in Australia).
- *Reliability of models and outputs*. The issue of model validation for evacuation applications is an open question, as will be briefly discussed in the following section. Even if a full direct validation exercise may prove difficult to carry out, it is essential to consider quantification and adequate communication of uncertainty in the model outputs to prevent misrepresentation of scientific results with potentially devastating consequences.
- *Models as decision support systems*. Ultimately, an evacuation modelling tool is a decision support system, designed to assist end users in their decision-making process by providing them with the best available modelling data and is not intended as a replacement for human decisions. This implies that model outputs must be presented in a manner that facilitates a clear interpretation of results and minimizes the risk of judgment errors. For an IC for example, this means being able to easily compare the outputs of different simulation scenarios in a scientifically robust manner, to quickly gain an understanding of which plan may be the most effective under the conditions considered, taking into account any uncertainties and unknowns factors.

We argue that the process of identifying these requirements necessitates an extensive consultative approach well before any software development begins. Throughout this process, all parties involved should develop three essential design documents: a user requirements document, which lists all requirements that the technology needs to address, a risk register outlining roles, responsibilities, and risk mitigation strategies, and a strategic roadmap defining the development path with a clearly defined end goal. Finally, these documents should be revisited as the developments progress, with ongoing testing and feedback provided by end users. Only through such a thorough consultative process can we bridge the current gap in the use of computational modelling for evacuation management.

A BRIEF REVIEW OF MODELLING LARGE-SCALE EVACUATION

As the number of evacuation models continues to grow, user experiences and needs are pivotal for broader adoption, spanning community, government, and industry. Lovreglio et al., 2020 conducted a comprehensive international online survey in 2018, primarily focusing on pedestrian and indoor evacuation models but with implications for traffic evacuation. The survey highlighted key factors influencing model selection, emphasising validation and verification (V&V), data output, model documentation, continual development, and software usability. Notably, V&V emerged as a significant concern, reflecting users' demand for trustworthy model outputs. However, applying V&V to large-scale outdoor scenarios, especially in the context of wildfires, proves challenging due to the less constrained spatial and temporal behaviour compared to structured evacuations from buildings. While existing V&V documents provide guidelines for specific contexts, the lack of universally applicable procedures remains a challenge. Efforts by organisations like the National Institute of Standards and Technology (NIST) (Ronchi et al., 2013, 2016) and the International Standardisation Organisation (ISO) (ISO, 2020) are progressing toward standardised protocols, but challenges persist in defining comprehensive and universally applicable V&V processes for evacuation models. Ronchi et al., 2023 contribute to this with a verification protocol for wildfire evacuation models, acknowledging the difficulties and proposing tests for accurate implementation of modeling layers. It is important to note that the survey work by Lovreglio et al., 2020 is highly valuable for indoor fires but may require adaptation for large-scale evacuations. Additionally, the survey's utility is reinforced by the inclusion of respondents from diverse backgrounds, including end users outside of academia, accounting for 234 participants from 41 countries and various professional domains. However, despite the insights provided by the survey, none of the covered models, including the pedestrian and building evacuation models, are currently being used for strategic planning, readiness, or response, underlining the ongoing challenges in applying these tools to real-world scenarios beyond academic and research contexts.

Notwithstanding, there are several simulation platforms for evacuation currently available. WUI-NITY, a modular simulation platform built on the Unity 3D game engine, effectively integrates fire, pedestrian, and traffic models to forecast evacuation behaviour during bushfire events (Kuligowski et al., 2022). This freely available platform allows for the simulation and visualisation of human behaviour, bushfire development, and evacuation scenarios. WUI-NITY's capability to import data from external wildfire models, such as FARSITE (Finney, 1998), and its implementation of a traffic model based on the Lighthill-Whitham-Richards (LHR) model (Li et al., 2012) contribute to its versatility. Recent studies, including a community drill in Roxborough, Colorado, and simulations of California wildfires, have validated WUI-NITY's performance, highlighting its potential for planning and real-time decision-making applications with its simplified yet effective models (Gwynne et al., 2023). The platform's modularity allows for the coupling of different sub-models, and its accessibility to a wide audience makes it a valuable tool for future model calibration and validation efforts.

There are other simulation platforms for evacuation currently available. SEEKER is a simulation platform integrated with an archetype-based behaviour model and employed by Victorian emergency services to understand community responses in bushfire evacuation scenarios (Marquez et al., 2022; Singh & Padgham, 2017; Singh et al., 2021). SEEKER takes as input fire progression simulation outputs from model like Phoenix and Spark (Faggian et al., 2017), a routable representation of the road network from Open Street Map, and a synthetic representation of individuals in the impacted area, and simulates community responses, considering various emergency response levers like warning messages and traffic control. Incorporating situation-based cognitive decision-making and MATSim traffic simulation, the platform provides detailed outputs on vehicles' trajectories and individuals' decisions during evacuations, including any intermediate trips to locations other than their final destinations. These outputs aid in identifying congestion bottlenecks, understanding diverse evacuation outcomes against a range of behaviour assumptions, and informing planning and preparedness. Simulation analysis supports operational decision-making, and the platform allows virtual testing of response strategies, including emergency messages and traffic control measures.

EXODUS is a suite of software tools designed for simulating the evacuation of large populations from various enclosures, including buildings, aircraft, and ships (Gwynne et al., 2006). Its core components include the Occupant, Movement, Behaviour, Toxicity, and Hazard sub-models (Galea & Galparsoro, 1994; Galea et al., 2000). The software employs rule-based descriptions, utilising heuristics to determine the progressive motion and behaviour of individuals. The Occupant sub-model in EXODUS characterises the response of individuals during evacuations based on their personal attributes (i.e., physical, positional, personal and hazard effects) influencing the individual's decision-making process and enabling the simulation to track their progress and behaviour during the evacuation process (Owen et al., 1996; Zhao et al., 2017). The Movement sub-model governs the travel speed of individuals during evacuations, taking into account factors such as terrain, obstacles, and queues (Gwynne et al., 2019). It assigns different travel speeds, such as run, walk, leap, and crawl, based on the specific conditions each evacuee encounters during the evacuation process. The Behaviour sub-model, influences occupants' responses and evacuation dynamics based on their attributes and environmental conditions (Galea et al., 1996). The Toxicity sub-model assesses the physiological impact of the environment on occupants, considering hazards like elevated temperature, thermal radiation, and toxic gases (Gwynne et al., 2001). The Hazard sub-model distributes hazards over time and location. EXODUS is well-suited for diverse applications, including planning, preparedness, readiness, response, emergency training, and community education. It provides valuable insights into evacuation scenarios and includes data analysis tools for effective result interpretation, as has been demonstrated in various publications (e.g., Galea, 1998; Gwynne et al., 2000).

DISCUSSION

Evacuation modelling is most useful for emergency management and planning when it supports the myriad of concerns of all stakeholders and incorporates realistic human behaviours and actions over idealised or optimised ones. Adoption of evacuation modelling capability for decision support involves a process of co-learning and co-production between emergency management stakeholders and technology providers. For emergency agencies to use evacuation models to inform decisions that impact lives, an often overlooked yet essential ingredient is time: required to understand, explore, adapt, and accept the modelling capability confidently into decision workflows. Model providers equally require time to shift evacuation modelling from a mathematical concept to a human-centred one.

The role of FBANs along with fire progression models in the emergency services is formalised and has existed for over a decade. FBANs are regarded with a high level of trust within teams, and that trust extends to the timeliness and quality of FBAN outputs (Begg et al., 2021). No such role exists in the predictive services for evacuation related modelling capability yet. This is partly because the need for evacuation planning is relatively new in Australia (Binskin et al., 2020; Teague et al., 2010) and current state-of-the-art evacuation modelling capability sits around Technology Readiness Level (TRL) 6 (technology demonstrated in a relevant environment), e.g., SEEKER (Singh et al., 2022), compared to fire progression models that have reached TRL9 (full system proven in operational environment), e.g., SPARK (Bally, 2023). Outside of technology readiness, other determinants of adoption of technology in emergency services include individual (e.g., perceived usefulness and ease of use, individual experience in emergency management), organisational (e.g., organisations IT infrastructure, interoperability and readiness, financial resources, decision-making processes), and contextual determinants (e.g., social norms and culture, and IT fitness for purpose) (Gulatee et al., 2020). Overcoming individual, organisational, and contextual challenges takes time, particularly in emergency management where reliance on technology for decisions that directly impact lives comes from trust, and the progression of technology over the final rungs to TRL9 is a necessarily slow process, and rightly so.

The Community-Based Bushfire Management program (Macken, 2019) is a successful example of a government funded program supporting emergency services and communities working together in Australia, in a community-led partnership to appreciate and plan for bushfire risk, understand roles and responsibilities, increase awareness and education, build trusting relationships, and ultimately improve safety in bushfires. Use of evacuation modelling to support these kinds of collaborative initiatives (see examples is Figure 2 and Dennis (2022)) shows promise in reaching a shared understanding and improving community resilience.

Compared with tools for modelling natural hazards like wildfires and floods, technology for modelling and simulating human behaviour during such hazards is relatively new. However, modern day computing infrastructure is rapidly enabling the use of this technology in tandem with natural systems modelling. We presented examples of the ways in which this technology is starting to be considered, beyond its obvious use in planning and preparedness, in also training and community education. What is unique here is a feedback loop that could positively alter community outcomes during natural hazards: since simulations of community and emergency responses today can help inform resilient behaviours of tomorrow.

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