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On the utility of shelters in wildfire evacuations

Kent Steer [a], Ermyas Abebe [b], Mahathir Almashor [b], Anton Beloglazov [b], Xu Zhong [b,*]

[a] Melbourne School of Engineering, University of Melbourne, Melbourne, VIC, 3010, Australia
[b] IBM Research Australia, 60 City Road, Southgate, VIC, 3006, Australia

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ABSTRACT

The combined challenges of a high fire risk and poor vehicle access in mountainous regions have led planners and emergency management authorities to consider non-traditional alternatives to complete evacuation of a region under threat. Community fire shelters have been put forward as one such alternative; however, their benefits remain contested. In this paper a series of experiments are designed in the Dandenong Ranges in Australia and presented to elucidate the relationship between shelters and community safety in wildfire scenarios. Our approach utilises a multi-stage simulation workflow to evaluate the outcome of 64 shelter configurations subject to three different fires. When compared to a scenario without shelters, some shelter configurations result in up to 10% reduction in the median exposure count, while some other configurations increase it. It is found that the efficacy of shelters strongly depends on the relative location to the ignition point and the trend of fire progression. The most effective shelters are identified for the specific fires that we simulate. The results demonstrate that sophisticated modelling and simulation is necessary for decision makers to determine a beneficial shelter placement strategy that remains effective across a number of likely wildfire spread scenarios.

1. Introduction

Wildfires cause catastrophic consequences on communities around the world resulting in environmental destruction and more importantly loss of life. As populations living within the Wildland Urban Interface [1–3] increase, more people fall at risk of wildfires that typically ravage these environments. The devastation of recent wildfires in Victoria — Australia in 2009 [4] and South California — United States in 2003 and 2007 [5] have demonstrated the need to better understand why the mitigation plans failed to protect the community in these events and improve community resilience.

Community responses to wildfires generally fall into two categories: *evacuation* and *shelter-in-place* [6]. In-place shelters can be divided into *refuge shelters* and *in-home shelters* [7]. Refuge shelters are often fortified buildings capable of protecting groups of people from an oncoming threat; they typically include shopping centres, warehouses, schools, and sports arenas. Sheltering in-home is usually associated with the 'prepare, stay and defend' strategy, where residents stay at their homes and actively defend the property. The 'prepare, stay and defend' policy was well implemented in Australia. Well-prepared houses were proved to be able to improve safety and reduce property loss in Australia [8,9]. Mccaffrey et al. validated the 'prepare, stay and defend' policy in four contextual areas in the United States [10]. The validity of the policy can be broken by the contextual differences between Australia and the United States. Careful groundwork is needed to effectively implement the policy in the United States.

Evacuations involve migrating a population to an area outside the region at risk. Evacuating populated areas exerts high demand on road networks, often leading to traffic congestion and consequently prolonged evacuation times. Evacuation may not always be optimal or even feasible in this situation, since the efficacy of evacuations is determined by the ability to clear a region before it is impacted by a threat. This is partly highlighted by prior works, which have derived the evacuation risk for a region as a function of the number of exit roads relative to the population size. E.g., Church et al. [11,12] and Cova et al. [13] applied the bulk lane demand analysis to identify high evacuation risk areas within the Western United States. Hence, strategies complementary to evacuation are required to mitigate the risk on populations, especially in areas with flow-restricted access.

On the other hand, sheltering-in-place involves evacuees seeking refuges inside safe structures within the area under threat. The use of shelters within at-risk areas has the potential to reduce unnecessary evacuations by providing safe locations within close proximity of residents. Hence the use of such shelters have been proposed as a

* Corresponding author.
E-mail address: peter.zhong@au1.ibm.com (X. Zhong).

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contingency option for regions where plans such as stay and defend, and leaving early cannot be implemented, e.g., townships in mountainous regions which often have a small number of exit roads [14–16]. However, while establishing shelters may have an intuitive appeal to both authorities and residents, their use has had mixed results historically [17–20]. Therefore, the consequences of shelters and other protective strategies should be thoroughly explored before being put to use.

In particular, the utility of shelters needs to be thoroughly investigated in situations where a local community is considering establishing a new shelter, or a region consisting of multiple communities is considering establishing multiple shelters. One consideration during such a study is an optimal placement of shelters. To this end, some previous works have looked at modelling the optimal positioning of shelters in flooding scenarios [21–24]; however, similar work for wildfire evacuations has not been done. While some conclusions have been reached about the effect of the number and capacity of shelters for hurricane and flood evacuations, the questions around the utility of shelters in wildfire disasters remain open. Cova et al. compared evacuation, shelter-in-refuge, and shelter-in-home in wildfires through simulation [7]. The trade-off between the three actions is complex and needs to be considered according to specific scenarios.

The core contribution of this paper is to investigate how the placement of *refuge shelters* changes the risk profile of a wildfire-prone region during a wildfire by leveraging a multi-stage workflow of wildfire/evacuation simulator. Specifically, the following research questions are addressed:

- Is it always true that establishing some shelters is better than none?
- What is the relationship between the presence of shelters and the risk of personal harm in wildfire evacuations?
- What are the factors that influence the utility of shelters, e.g., number of shelters, number of people within range, location relative to fire progression, distance to the fire ignition point?

The introduction of a shelter in a region may distort the travel patterns in an evacuation scenario. This paper posits that this distortion can potentially lead to undesirable protective outcomes. During evacuations, the existence of popular destinations, such as shelters within an area at-risk, has the potential to focus traffic. This in turn may elevate the egress time and evacuation risk of residents heading to these shelters. In addition, in the case where a shelter is located near a major access road, any congestion could lead to increased risk for the through-traffic. Our simulation casts new light on understanding the complexity of selecting effective shelter locations in high-fire-risk area across a number of likely wildfire spread scenarios.

The remainder of the paper is organised as follows. Following the review of relate work in Section 2, an overview of the models of the simulation workflow, first described in Ref. [25], is given in Section 3. Sections 4 and 5 present the experimental design and results, respectively. Section 6 discusses the results and the implications of the discoveries in this paper. Finally, Section 7 provides the final conclusions.

2. Related work

Southworth [26] described evacuation modelling as a five step process involving traffic generation, departure time modelling, destination selection, route selection, and evacuation plan analysis and revision. The destination selection aspect refers to the allocation of safe endpoint locations to evacuees as a part of the modelling process. The selection of such endpoints could be determined in one of four possible ways, based on: (1) the closest exit from the area at risk (in terms of distance and/or expected travel time); (2) the location of relatives and friends; (3) pre-planned evacuation destinations; or (4) the real-time traffic situation (congestions, detours) at the time of the evacuation. The availability of refuge shelters adds another potential destination type, thus requiring additional modelling.

The use of refuge shelters (further referred to as *shelters*) raises a number of interesting questions, including: How does their presence impact the dynamics of traffic flow and consequently, the protective outcomes? How can the assignment of evacuees to shelters be optimised to reduce evacuation times and risk of personal harm? The allocation of evacuees to appropriate shelters has been a focus of prior research, which generally falls into one of three categories: (1) coordinated system-optimal assignments; (2) uncoordinated myopic assignments; and (3) a hybrid strategy.

In system optimal assignment models (work by Sherali et al. [21] and ElDessouki [22]) the allocation of evacuees to shelters, as well as the routes to these shelters, are optimised to minimise the overall evacuation time. While such approaches might help establish best case outcomes, they do not account for real-world scenarios where evacuee objectives could notably diverge from the optimal system assignments.

On the other hand, uncoordinated or myopic evacuation models allow for scenarios wherein evacuees themselves determine both the shelter to evacuate to, and the specific routes to take. Kongsomsaksakul [23] modelled this approach as a bi-level optimisation problem. At the top-level, the system determines which shelters out of an admissible set should be used, while at the bottom-level, evacuees decide which shelter to go to and which route to take given the locations and capacities of shelters. This bi-level optimisation problem is then solved using a genetic algorithm. While the approach does not yield optimal outcomes, it is more representative of real-world evacuations.

Ng [24] proposed a hybrid approach, where the system determines an optimal evacuee-to-shelter assignment and then allows the evacuees to select the routes to shelters. The approach provides closer to optimal protective outcomes compared with uncoordinated approaches while also accounting for unforeseen real-world events (such as road-blocks and detours) that could cause evacuees to take alternative routes. However, such enforcement of destinations for all the evacuees may not be feasible in real world.

In this paper, we adopt a similar model to that proposed by Kongsomsaksakul [23], where the locations of shelters are selected by an authority, while the evacuees make their own decisions on the choice of destinations and routes. We believe that this model is a reasonable representation of reality and allows us to conduct realistic analysis on the utility of shelters.

Considering this model, a number of interesting questions about *refuge shelters* emerge. Specifically, does the presence of shelters always offer better protective outcomes? How is the utility of a shelter dependent on the specific progression of the oncoming threat? Are there general location factors that influence the utility of a shelter? What are the impacts of placing shelters, both on the local and global level? For example, could a shelter improve evacuation times for a subregion, but worsen clearance times for the overall region?

In general, these questions have not been thoroughly explored. Sherali et al. [21] and ElDessouki [22] studied the effects of shelter placement under system optimal assignments for flood and hurricane scenarios and found that the placement of shelters has an impact on the evacuation times. However more concrete conclusions on what factors influence the utility of shelters have not been discussed. Kongsomsaksakul [23] performed similar studies for uncoordinated evacuation scenarios and found that more shelters improve evacuation times up to a certain point (7 shelters in the specific scenario considered) after which the performance degrades. Their study into the capacity of shelters also identified that low capacity shelters require higher number of shelters which in turn increases the evacuation time.

However, as discussed above, a number of open questions on the utility of shelters remain. This study aims to address these questions. Specifically, the paper addresses whether shelters provide a better protective outcome under all scenarios; what spatial factors influence the utility of shelters; and how the utility of a shelter is influenced by the specific threat progression.