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Enhancing emergency evacuation response of late evacuees: Revisiting the case of Australian Black Saturday bushfire

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This paper develops a multi-objective integer programming model to support tactical planning decision-making during a short-notice evacuation using the situated context of the 2009 Black Saturday bushfires in Victoria. Various bushfire scenarios and sensitivity analysis considering short time windows, availability of resources and road disruptions were implemented to demonstrate the robustness and reliability of the model. The ε-constraint technique was applied to solve the problem. Results showed that it would be possible to evacuate all late evacuees during the Black Saturday bushfire events, even if one or two resources are disrupted within the hard time window constraint.

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1. Introduction

Bushfires (wildfire) are a natural hazard that constantly threatens human lives and properties in Australia. In the past 150 years, bushfires have claimed hundreds of lives and resulted in billions of dollar worth of damage in Australia. During this period, 300 people have lost their lives and a further 4185 have suffered injuries in Victoria alone. These figures account for approximately 39 per cent of total deaths and 57 per cent of injuries from all major recorded natural disasters in Australia's history (Haynes et al., 2010). The Black Saturday bushfires, which occurred on the 7th of February 2009 in Victoria, are the worst on record. 173 people lost their lives, more than 7500 were displaced, and an estimated $ 4.5 billion worth of financial losses were incurred (Teague et al., 2009).

Evacuation is defined by the Emergency Management Australia (2005) as "a risk management strategy which may be used as a means of mitigating the effects of an emergency or disaster on a community. This process involves the movement of people to a safer location and to be effective it must be correctly planned and executed". Bushfire evacuation can be mandatory, recommended or voluntary. In Australia, it is voluntary as people are permitted to stay and protect their houses and possessions during an emergency (Teague et al., 2009). There are three categories of people in an event of emergency: (i) those who leave early; (ii) those who decide to shelter in refuge and (iii) those who stay at their properties (i.e. Shelter-in-Place). They are also referred as 'protective actions' (Cova et al. (2011). This research focuses on the evacuation of the third group of people as late evacuees in a short-notice evacuation situation. The situated knowledge uncertainty of a short-notice evacuation may put evacuees' lives at a greater risk. 32 per cent of all the bushfire fatalities in Australia (176 of 552 deaths) during the last century were related to short-notice evacuation. Data shows that over 50 per cent of those who were

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evacuated on Black Saturday were late evacuees (Haynes et al., 2010). The Victorian Bushfires Royal Commission (VBRC) highlighted the need for amendments by providing 67 recommendations in their final report to the Victorian Government in July 2010. The VBRC emphasised the importance of urgently developing emergency bushfire plans and improving the emergency evacuation components within these plans, such as the identification of candidate shelters and bushfire disruption risks. These recommendations were given serious consideration when developing the national bushfire policy: *Prepare, Act, Survive* (Australasian Fire Authorities Council, 2010).

A short-notice evacuation during emergency is a costly, complex, disruptive and politically sensitive issue. Short-notice evacuation of late evacuees is often challenging as it is dependent on numerous uncertainties. It is also an unavoidable as there are people those who choose to stay and defend their properties instead of leaving early; those with disability, those with younger children, and the elderly and those with no access to a personal vehicle. They are heavily dependent on fire agencies for last-minute evacuation. While early evacuation often occurs by car, the short-notice evacuation to transfer people from assembly points to the nearest safe shelters typically is carried out using high-capacity vehicles such as buses (Vuchic, 2005). Compulsory evacuation warnings are broadcasted to inform late evacuees to assemble at a pre-defined location and prepare for evacuation to a safer shelter via organised rescue vehicles.

Lessons from the 2009 Black Saturday bushfires in Australia highlight the importance of both strategic and tactical planning to enhance operational efficiency of transit-based, short-notice emergency response. Given the uncertainty of bushfire propagation and the resulted network and supply disruptions, the transfer of people from bushfire-prone areas to safe shelters within a short-time window has remained a key challenge for emergency service agencies. Simultaneous decisions are to be made in bushfire situations to assign and allocate evacuees to safe shelters, selecting the right evacuation vehicles and choosing the optimal route. These decisions are to be optimised considering risk and cost minimisation, efficient resource utilisation, while at the same time maximising the safety of evacuees. The development of a decision support system capable of simultaneously considering multiple objectives and constraints under various bushfire scenarios is urgently needed to effectively respond to the perennial threat of bushfires in Australia. Hence, this study aims to develop a multi-objective integer-programming model to tackle the key operational challenges associated with timely evacuation, shelter assignment and routing in a short-notice evacuation during bushfire events. The model's parameters are based on real observations from the Black Saturday bushfire events to mimic the potential impact of observed risk of network disruptions and the available clearance time on resource allocation. The developed model is an integer program with two objectives – maximising number of evacuated people using the safest routes and optimally determining the number of shelters and the required number of vehicles. The model therefore considers capacitated multi-location, multi-routing, and multi-vehicle types (high and medium capacity vehicles). A solution approach based on ε-constraint method is implemented in the model.

Section 2 of this paper presents the literature review. This is followed by a brief description of the short-notice evacuation problem in Section 3. Section 4 introduces the mathematical model formulation. Section 5 offers the solution approach, along with a discussion of the computational results and practical implications of the model. Finally, Section 6 presents the key findings and conclusions.

2. Understanding the late evacuation procedures

An emergency evacuation system is a set of procedures and processes that guide the systematic evacuation of evacuees from disaster-affected areas to safe shelters. It is a complex, multi-component system, which requires multi-agency response to an emergency. Fig. 1 illustrates the interrelated and interlocking sequences and procedures involved in a typical emergency response. The system contains four major stages: (I) disaster (bushfire) impact evaluation (II) evacuation estimation (III) evacuation plan generation and (IV) evacuation plan implementation. In stage (I), the scale, intensity and magnitude of a bushfire are evaluated. This step requires the initial inputs (e.g. affected areas, bushfire direction, and transportation network data) to evaluate the potential threat of a bushfire for the next steps. Stage (II) estimates the operational inputs, which include the number of late evacuees, the optimum location of candidate shelters (based on capacity, accessibility and other risk factors), accessibility of routes and most importantly the time window. Stage (III) generates evacuation plans and actions, including help assign rescue vehicles, allocation of shelters, and identification of the safest and shortest routes. Generated plans are re-assessed and moderated by decision-makers in terms of feasibility and soundness in responding to real world situations. Finally, in stage (IV), the generated evacuation plans are implemented by emergency service agencies including broadcasting evacuation-warning messages, transferring evacuees to shelters, assignment of vehicles, and delineation of routes.

In evacuation planning, the decision of individuals/households plays a critical role. The ability to anticipate and estimate the number of people who potentially decide to leave early or stay in the area to protect property has a strong bearing on evacuation planning and resource allocation (Lindell et al., 2011). There are a wide range of behavioural factors that influence the evacuation decisions, including the age; physical capacity, mobility and health; responsibility of children, pets and livestock; and perception of risk and the degree of preparedness. Murray-Tuite and Wolshon (2013) developed one of the most comprehensive evacuation models in which a broad range of behavioural parameters were incorporated. Their research identified key factors that influence evacuation decision-making. However, these factors were considered in modelling only in specific types of disaster such as hurricanes (Hsu and Peeta, 2013; Pel et al., 2012). Only a few studies have considered incorporating these factors in routing or resource allocation modelling.

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