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Possibilistic scheduling routing for short-notice bushfire emergency evacuation under uncertainties: An Australian case study ☆

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ABSTRACT

This paper aims to develop a capacitated vehicle routing solution to evacuate short-notice evacuees with time windows and disruption risks under uncertainties during a bushfire. A heuristic solution technique is applied to solve the triangular possibilistic model to optimise emergency delivery service. The effectiveness of the proposed algorithm is evaluated by comparing it with a designed genetic algorithm on sets of 20 numerical examples. The model is then applied to the real case study of 2009 Black Saturday bushfires in Victoria, Australia. The results show that it is possible to transfer the last-minute evacuees during the Black Saturday bushfires under the hard time window constraint. Network disruptions however have impact on resource utilisation. The modelling outputs will be useful in the development of emergency plans and evacuation strategies to enhance rapid response to last-minute evacuation in a bushfire emergency.

1. Introduction

A wildfire, commonly known as bushfire in Australia, is a freely burning, uncontrolled and unplanned fire, which often occur in rural and regional areas [11]. Bushfires are generally considered as a natural hazard but it is associated with arson with malicious intent. Bushfire in Australia has become a recurrent and seasonal phenomenon. Unfortunately, bushfire risk in Australia is rising and the costs of bushfire related disasters are mounting. This poses significant planning challenges for emergency services agencies to respond efficiently and effectively to bushfire threats. Over the past decades, Victoria, a state in the South East Australia with Melbourne as a capital, accounts for 39% of deaths and 57% of injuries of the total major natural disasters in Australia [29]. The 2009 Victorian Black Saturday bushfires were the worst on record, both in Victoria and Australia. Approximately 400 out-of-control fires killed 173 and injured 414, displaced approximately 7500 residents, and caused about $4.5 billion worth of damage [71]. The United States of America, Canada, Russia and few Asian and European countries also regularly experience wildfires.

Wildfires are difficult to control as they propagate rapidly and randomly. Bushfires continue to threat human lives and livestock. They disrupt vital infrastructure such as road and rail networks and destroy properties. Wildfires could escalate in intensity and magnitude with a slight change in environmental conditions, such as the wind direction and speed or topographic variability. Bushfires, for instance, can spread at a rate of 47 kilometres per hour, blaze heights can reach over 30 metres, and the radiant head temperature can escalate more than 800 °C (Victorian Bushfires Royal Commission Report, 2009, [78,82]).

People facing a bushfire are provided the option to evacuate early and seek refuge in a shelter [19]. However, there are residents who prefer to stay and defend their properties till the last minute [71]. In some countries such as Australia and in the southern regions of France, residents are legally permitted to remain and defend their properties [5]. However, in a situation of an extreme wildfire, a national emergency is declared which permits emergency service agencies to evacuate all people via a mandatory evacuation order. Evacuation is also required for people with special needs who have restricted mobility, such as children, the elderly and the households without a personal vehicle.

Late evacuation during a bushfire must be effectively planned in order to minimize risk of fatality or injury. Factors such as radiant heat, toxic smoke, disorientation, poor visibility, and increased threat from shelter and road disruption potentially place the life of stranded residents at a greater risk. For many years, private cars are the predominant mode to rescue people from bushfire affected areas [79]. While Pel et al. [52] recognised the use of private cars as an effective mode for early rescue, nonetheless the use of personal vehicles can exacerbate road

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congestion, makes the relief coordination more difficult and increases risk and uncertainty (abdelqawaed et al. 2010). Vuchic [79] found that the use of high capacity vehicles substantially reduces the coordination effort, reduce costs through consolidation, and improves the evacuation process. For example, a single bus-only highway lane can carry up to six times more passengers than the passenger car-only highway lane [39].

Late evacuation accounted for 32% of all fatalities in Australia during the period from 1900 and 2008 [29]. Despite the early warning, more than 50% of Black Saturday evacuees left their homes within 30 minutes of the bushfire reaching their properties (Victorian Bushfires Royal Commission Report, 2009). The Victorian Bushfire Royal Commission reported that 14% of the fatalities on Black Saturday were evacuees who attempted to escape bushfire via roads which were affected by fires. This late evacuation has resulted in severe injuries and fatalities particularly when residents exit bushfire affected areas. The stranded evacuees while in-transit had encountered toxic smoke (74%), subjected to fallen embers (59%) and flames (56%), struggled in wayfinding due to poor visibility (56%), obstructed by fallen trees (37%) and experienced delay due to heavy traffic in key intersections and arterial roads (30%). These statistics highlight the dangers of unorganised and unplanned last-minute evacuation using private vehicles.

The Victorian Bushfires Royal Commission (VBRC) has made 67 policy amendment recommendations in its final report to the Victorian Government [71]. Among them is the development of an emergency bushfire evacuation plan including resource allocation and shelter assignment. These VBRC recommendations are now the key elements embedded in the recently announced national evacuation policy, called Prepare. Act. Survive. (P.A.S.) (Australasian Fire Authorities Council, 2010 [7]). Despite this policy response, the execution of late evacuation plan remains problematic and challenging due to logistics complexity, multi-institutional coordination, environmental instability and uncertainty. The task of transferring evacuees from bushfire affected areas to safe shelters within a short notice time window through safe routes therefore continues to pose numerous challenges for emergency and rescue service agencies. The emergency response to a bushfire disaster becomes more difficult when the resources are finite and the relief supply chains are vulnerable to disruption. A modelling technique that is capable of simultaneously considering multiple objectives and constraints under a range of disruption scenarios therefore is required to effectively and efficiently respond to the threat from bushfires.

The major challenge for emergency response authorities, furthermore, is that multiple factors which are uncertain in nature, need to be considered in emergency evacuation planning. In some scenarios, it may be difficult to frame the problem parameters as exact values, due to insufficient historical data available to analyse. In other situations, data and probability distributions may be very time-consuming and difficult to source (e.g., patterns of wildfire propagation). In addition, time window calculations for each town tend to be difficult to model deterministically. Instead, they should be represented by interval ranges. In addition, travel time from designated assembly points to safe shelters may often be imprecise, especially when considering evacuation disruption scenarios (e.g., based on past experience, it may be "optimistically 35 minutes and pessimistically 55 minutes", "between 35 and 55 minutes", or "around 1 hour". Other parameters, such as evacuee population, available time windows and shelter capacities, are also often difficult to precisely determine. Triangular fuzzy numbers are used to satisfy the above uncertainties in emergency evacuation planning, as assigning a set of crisp values to ambiguous parameters is not appropriate. It is argued that using such sophisticated methods in real-time evacuation planning decisions would save both time and money, achieving two major objectives of evacuation management systems [26].

This research therefore aims to develop a reliable, integrated optimisation model to improve the efficiency of a short-notice emergency response to bushfire. The proposed mathematical modelling approach seamlessly and simultaneously maximises the number of late evacuees to be safely transported to operational shelters within the available time window through the shortest and safest routes using the most efficient vehicles.

The remainder of this paper is organized as follows: Section 2 presents the existing body of knowledge in the area of emergency evacuation modelling and management. Related research literature are collated and reviewed in order to identify key operational challenges and the existing approaches, methods and techniques to solve the evacuation problems. This is followed by Section 3 where a brief description of the problem is provided. Section 4 introduces the development of the mathematical model formulation for optimizing the evacuation decisions. Section 5 presents the heuristic approach to solve the model. Section 6 outlines key data from the 2009 Black Saturday Murrindindi Mill bushfire in Victoria, Australia. This data is subsequently used as the case study to test the model capabilities in Section 7. Finally, Section 8 concludes this study by summarising the key findings, major limitations and areas of future research.

2. Literature review

Emergency evacuation, in a disaster situation, refers to the provision of transferring evacuees from disaster affected areas to safer and protected shelters. Lindell [38] developed a comprehensive seven-stage evacuation framework to reflect myriad operations and emergency responses from a pre-disaster to post-disaster stage. Response time or clearance time is one key component of this framework, which involves the transfer of evacuees to safe shelters. The Australian Evacuation Framework (2005) however simplifies the process by identifying five-decoupling points: decision, warning, withdrawal, shelter and return. These decisions require issuing warning messages or in some cases a mandatory evacuation order, setting up assembly points, and transfer of evacuees to established evacuation shelters. The decision-making also varies for early, short notice and no-notice evacuation, each of which necessitates different operational responses. Early evacuation is often self-organised; whilst the short-notice evacuation requires operational planning by emergency service agencies. No-notice evacuation, on the other hand, requires a rapid response to identify, move and safeguard evacuees at a high-risk due to the time constraint. Self-evacuation however does not necessarily follow these stages. Since the evacuation is not mandatory in Australia, it thus provides options for people to stay and protect their properties. Consequently, this protective action to stay and defend could expose people to the threat from bushfires. The short-notice evacuation therefore is a systemic problem in Australia, which exerts significant strain on impromptu resource allocation and agile operational planning.

There is an extensive body of literature on emergency evacuation, which incorporates various inter-connected components of an emergency risk management framework such as prevention/mitigation, preparedness, response and recovery. Evacuation however is largely related to emergency response, which operationalises safe relocation of evacuees to protected and less vulnerable shelters within a restricted time window. The response to short-notice evacuation is dependent on various operations such as an emergency declaration, warning messages, registration and tracing, resource mobilization and search and rescue. Short-notice evacuation is therefore not a discrete operation; it is rather

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