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Robust stochastic vehicle routing and scheduling for bushfire emergency evacuation: An Australian case study

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A R T I C L E I N F O

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A B S T R A C T

This study proposes a stochastic modeling approach as an evacuation decision support system to determine the required vehicles, scheduling and routes under uncertainties in evacuee population, time windows and bushfire propagation. The proposed model also considers road availability and disruptions. A greedy solution method is developed to cope with the complex nature of vehicle routing problem. Furthermore, the effectiveness of the proposed solution is evaluated by comparison with a designed genetic algorithm on sets of various numerical examples. The model is then applied on the real case study of the 2009 Black Saturday bushfires in Victoria, Australia. Several plausible evacuation scenarios are generated, utilizing the historical data of Black Saturday. The results are analyzed using the frequency approach to determine the optimal evacuation plan. The results show that it would have been possible to evacuate the late evacuees on Black Saturday, even within hard time windows and a maximum population.

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1. Introduction

A wildfire, known as a bushfire in Australia, is a freely burning, uncontrolled and unplanned fire often occurring in regional areas, but which can also consume houses or agricultural resources (CFA Definitions, 2012). Uncontrolled bushfires can lead to loss of human lives as well as widespread damage to property, buildings, livestock, crops and road networks. Bushfires tend to be more prevalent in countries with harsh weather conditions like Australia, the United States, Canada and Russia. Factors such as global warming and climate change will potentially create more conducive conditions for bushfires in the future. The spread of a bushfire is influenced by the strength and direction of wind, and the surrounding landscape. The propagation rate can double for example with only a slight increase in wind speed and with a ten degree rise in land slope. Temperatures during a bushfire can exceed 800 °C, with flames potentially reaching heights of 30 m or more (Whittaker et al., 2009). Bushfires in Australia caused A$2.5 billion worth of damage between 1967 and 1999. 223 bushfire deaths were recorded during the same period, accounting to 39% of all natural disaster-related deaths in Australia. A$4.4 -billion worth of damage was caused by the 2009 Black Saturday In addition, 173 people lost their lives and a further A $645 million was incurred by survivors as injury-related expenses (Victorian Bushfires Royal Commission Report, 2009). Evacuation is defined as the procedure for moving people from a target location (an arranged meeting point) to a nearby safer location (Southworth, 1991). This can be a complex process with multiple considerations. "Evacuation strategies" are the most common method for controlling natural disasters and attempting to ensure the safety of affected people

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(Southworth, 1991). Bushfire evacuations can be mandatory, suggested, or optional. Most nations, including Australia, only require mandatory evacuation in extreme bushfire circumstances (Arnol, 2007). Instead, affected people are usually left to decide for themselves whether they want to evacuate or stay to try and protect their properties. Th decision is therefore a crucial in terms of community safety in a bushfire scenario. Affected people may decide to evacuate, shelter-in-home or take shelter-in-refuge nearby (Lindell and Perry, 1992). In terms of protecting human life, early evacuation is obviously the safest option. Early evacuation is particularly important for the disabled, the elderly, and people without transport. Speed of evacuation is a critical consideration in evacuation crisis management. High passenger-capacity public vehicles such as buses should therefore be available at assembly points as part of an evacuation strategy (Vuchic, 2005). However, the desire among affected people to stay and protect properties in a bushfire scenario is often very strong. As a bushfire's intensity increases, so too does the potential for factors such as road network blockages, radiant heat and toxic smoke to impact evacuation efforts. Time is always a crucial consideration. Evacuation strategies should attempt to ensure the maximum potential number of evacuees using a finite number of vehicles within the available clearance times (time windows). They should also consider landscape patterns and a range of bushfire scenarios contingencies such as sudden changes in wind direction. Such factors potentially affect evacuation cost, transport network links and associated travel times. There is also the potential that these factors may disrupt the evacuation operation to the extent that human lives may be lost). Contingencies must be considered in emergency evacuation planning because multiple factors are uncertain in an emergency evacuation situation. In bushfire scenarios, insufficient historical data and the multiple potential patterns of propagation often make it difficult to frame the problem parameters as exact values. In addition, time windows for affected locations tend to be difficult to deterministically model. Accordingly, interval ranges are a more appropriate means of representing time windows for a bushfire evacuation scenario. To minimize the potential loss of human life, an integrated optimization model evacuation routing approach needs to be developed that can consolidate the dynamic components of an emergency bushfire evacuation scenarios. This paper presents a stochastic logistics mathematical modeling approach to enable effective planning for short-notice emergency evacuation operations. The model enables planning to be conducted for transporting the maximum number of late evacuees to safe shelters via using available resources i.e. vehicles and shelters, within a short time window. The model's objective function is to maximize the total number of evacuees within very tight pre-determined time windows, assuming road block conditions. The main contributions of this study is to consider uncertainty (stochastic) and robustness of evacuees demands and time windows during an emergency situation. In order to address the inherent uncertainty in an emergency evacuation scenario, the evacuation plans for 1000 plausible scenarios from the 2009 Black Saturday bushfire are analyzed and solved by the proposed greedy algorithm.

The remainder of this paper is organized as follows: Section 2 surveys existing research literature on emergency evacuation and VRP problems; Section 3 introduces the proposed mathematical formulation; Section 4 introduces the 2009 Black Saturday case study; Section 5 provides computational results using the 2009 Black Saturday bushfire data and plausible evacuations scenarios; and in Section 6 conclusions will be drawn.

2. Literature review

The vehicle routing problem (VRP) tries to determine the optimal routes for a vehicle fleet to service sets of customers (Dantzig and Ramser, 1959). The majority of existing research literature has investigated VRP variations, providing insights such as introducing exact solution approaches and greedy solution algorithms (Eksioglu et al., 2009). In this paper, several variants of classic VRP are utilized and consolidated:

(1) Capacitated VRP (CVRP), where vehicles have a limited, pre-defined capacity. (2) Multi-destination VRP (MDVRP), where vehicles can visit a destination more than once. (3) VRP time-window (VRPTW), where a time window limitation is introduced within which vehicles must service customers. (4) Dynamic VRP (DVRP), where problem elements such as the availability of a road network may vary over time. (5) Stochastic VRP (SVRP), where random uncertainties are involved.

Stochastic programming (SP) is an appropriate planning tool for emergency evacuation because it can handle uncertainty via probabilistic disaster and outcome scenarios. SP has been successful applied to many disaster management problems (Barbaroso and gcaron, 2004; Beraldi et al., 2004; Chang et al., 2007; Lamiri et al., 2008).

Stochastic vehicle-routing problems (SVRP) are divided into two types: 'wait and see' and 'here and now' (Dror et al., 1989). In 'wait and see' problems, routes are determined after demand is known. They tend to become deterministic vehicle-routing problems (DTVRP). In 'here and now' problems, routes are set based on expected demand, and this type of problem is the focus of our study, using a chance-constrained model (Stewart and Golden, as cited in Dror et al. (1989)). Under the chance-constrained model, the selection of routes is strictly based on probable demand and time windows. 'Here and now' problems are also referred to as probabilistic optimization (Joshi, 1997) or priori optimization (Bertsimas et al., 1990).

'Here and now' SVRP problems can be further embellished as stochastic location-routing related problems (SLRP). Integrating other VRP variants to SVRP increases the complexity of the problem. Satisfactory solution procedures for these problems are still evolving as a result (Bertsimas et al., 1995). It is far easier to solve the deterministic version of a problem than every instance of its probabilistic formulation.

From other perspective, few studies have investigated the use of operations research techniques in natural disaster evacuation routing problems (Cova and Johnson, 2003). There is also limited published research on the applications of VRP mod-

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