Optimizing Transit Planning for the Evacuation of Vulnerable People During Natural Hazards

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Abstract

The impact of natural hazards is becoming increasingly severe, significantly affecting various parts of the world. Disasters affect individuals differently, with certain groups being more vulnerable and at greater risk. One significant concern during natural hazards is transportation planning of transit vehicles that may include road closures, time constraints, and traffic congestion. Various transportation modes, including emergency buses and ambulances are utilized to transfer people from disaster-stricken areas to safe shelters. We address the problem of scheduling and routing transit vehicles to transport vulnerable individuals from affected areas to shelter locations within specified timeframes. This is formulated as a vehicle routing problem with the objective of minimizing total evacuation time. Computational findings are shown through a case study in New South Wales.

Figure 1. The Role of Transit-based evacuation planning during Natural Disasters.

Introduction

Disasters are conventionally overseen through four distinct phases: prevention, preparedness, response, and recovery. Disaster preparedness and response operations management encompasses the planning of evacuation routes and the establishment of relief shelter locations to safeguard individuals from the adverse effects of disasters in the impacted region. Evacuation pertains to the procedure in which individuals leave their residences to seek safety during times of disaster (Mojtahedi and Oo, 2017).

In the context of evacuation planning, Wolshon et al. (2005) provided a definition of vulnerable individuals as potential evacuees, encompassing "special needs" groups like the elderly, infirm, impoverished, homeless, orphaned, incarcerated, indigenous, and tourists.

Although personal transportation might be relatively efficient under normal conditions, it presents significant challenges for emergency management authorities dealing with vulnerable populations (see **Figure 1**). This could be due to the lack of car access among these groups, leading to their categorization as "low mobility". Reports indicate that local governments often face deficiencies in transportation resources and inadequate planning when it comes to evacuating individuals who are considered vulnerable during disasters (Freire and Stren, 2001).

This research aims to improve evacuation planning for vulnerable individuals during disasters in the context of optimization of transit vehicles routing.

Conceptual framework

A research conceptual framework for this study is proposed in **Figure 2**, drawn primarily from the literature. As this figure shows, the broader area of this study begins with the disaster management theme, then focuses on emergency humanitarian logistics planning, and specifically on evacuation operations in post-disaster logistics planning. The main contribution of the research lies in developing decision-making models using operations research approaches for post-disaster evacuation planning. Mathematical modelling and optimization methods for evacuation issues have received less attention compared to other approaches, particularly in the context of supported evacuation or transit-based evacuation planning problems.

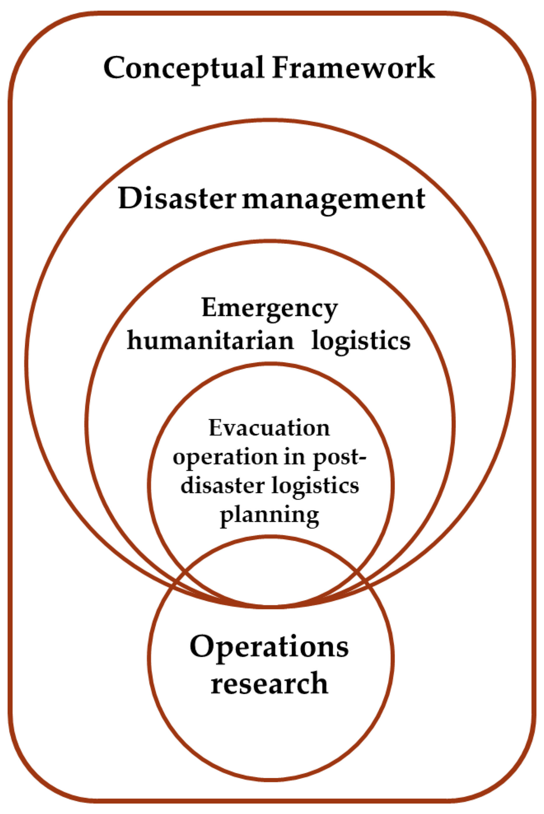

Figure 1. The Role of Transit-based evacuation planning during Natural Disasters.

Problem description

Transit-based evacuation planning is focused on transporting vulnerable individuals, with limited access to private cares, from affected areas to safe shelters within strict time constraints. These plans can be formulated through mathematical modeling approaches, sharing similarities with vehicle routing problems. This study proposes a two-stage scenario-based mixed-integer stochastic scenario-based programming mathematical model. In the first stage, the model determines the optimal allocation of emergency vehicles to vehicle depots (z_{kiv}^{start}), and allocation of evacuation centers to the shelters (x_{ij}). In the second stage, it optimizes vehicle routing and scheduling in various disaster scenarios (y_{ijvcs}). These scenarios encompass different predicted disaster impacts on the transportation network and their likelihoods, involving factors such as road closures, rendering some parts of the network inaccessible and significantly impacting travel times. Although the likelihood of these disaster scenarios is typically low, their impact can be devastating, constituting disruption risks. Consequently, we formulated the objective function of this problem using the total evacuation time via the Conditional Value at Risk (CVaR) measure (T_{CVaR}^{max}), renowned for its ability to quantify disruption risks. **Figure 3** illustrates the considered problem in a sample transportation network in which emergency vehicles depart from depots, picking-up evacuees from evacuation centers and transporting them to the shelters through the safest and fastest routs.

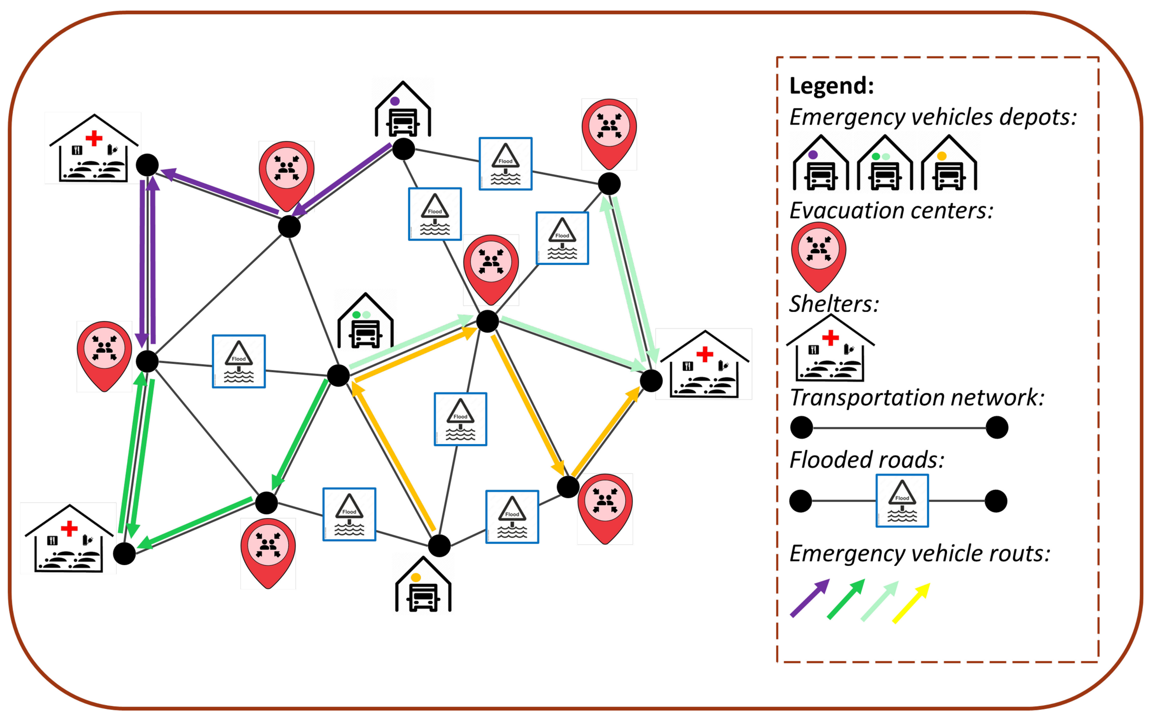

Figure 3. Schematic representation of the considered problem.

Mathematical modeling

The transit-based evacuation planning mathematical model in this study is formulated based on the main assumption like (Bish, 2011) and (Goerigk et al., 2013) with minor modifications. It is assumed that the location of vehicle depots ($k \in K$), evacuation centres ($i \in I$), shelter locations ($j \in J$) are predefined. Travel times in the transportation network parameter (t_{ijs} and tg_{kis}^{start}), evacuation demand (e_{is}), and receiving capacity at shelters (b_{js}) are scenario-based input data while vehicle capacities are scenario dependent (cap_v). Basic components of the proposed model is as follows:

- Objective function-minimizing worst-case scenario for total evacuation time:

$$Min\ T_{CVaR}^{max} = VaR + \frac{\sum_{s=1}^{S} p_s \,.\, tl_s}{1-\alpha}$$

- Shelter allocation constraints:

$$x_{ij} \le \sum_{v=1}^{V} \sum_{c=1}^{C} \sum_{s=1}^{S} y_{ijvcs}\ ; i \in I, j \in J$$

$$\sum_{j=1}^{J} x_{ij} \ge 1; i \in I$$

- Vehicle allocation constraints:

$$\sum_{k=1}^{K} \sum_{i=1}^{I} \sum_{v=1}^{V} z_{kiv}^{start} \le 1$$

- Vehicle scheduling and routing constraints:

$$T_s^{max} \ge \sum_{c=1}^{C} (tg_{vcs} + tb_{vcs}) + \sum_{k=1}^{K} \sum_{i=1}^{I} tg_{kis}^{start} . z_{kiv}^{start}\ ; v \in V, s \in S$$

$$tg_{vcs} = \sum_{i=1}^{I} \sum_{j=1}^{J} t_{ijs} . y_{ijvcs}\ ; v \in V, c \in C, s \in S$$

$$tb_{vcs} \ge t_{ijs} . \left(\sum_{i'=1}^{I} y_{i'jvcs} + \sum_{j'=1}^{J} y_{ij'v(c+1)s} - 1 \right); v \in V, c \in [C-1], s \in S, i \in I, j \in J$$

- Capacity constraints:

$$\sum_{j=1}^{J} \sum_{v=1}^{V} \sum_{c=1}^{C} cap_v . y_{ijvcs} \ge e_{is}; i \in I, s \in S$$

$$\sum_{i=1}^{I} e_i \,.\, x_{ij} \le b_{js}; j \in J, s \in S$$

- CVaR constraints:

$$tl_s \ge T_s^{max} - VaR;\ s \in S$$

Discussion and conclusion

In this research, a novel two-stage stochastic scenario-based model is developed to provide insights for emergency managers, enabling them to make informed decisions about the transit-based evacuation planning problem. The problem setting under consideration determines the allocation of transit vehicles to vehicle depots, as well as the allocation of evacuation centers to shelters before the occurrence of any disaster as a mitigation strategy. Additionally, the developed model outlines vehicle scheduling and routing for specific scenario realizations as part of the response strategy. The obtained results are robust against worst-case scenarios with the help of the CVaR framework.

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