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Strategic Evacuation Network Design (SEND) under cost and time considerations

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ABSTRACT

In this study, we pose and analyze an evacuation network design problem to provide a planning tool to help with high-level design decisions involved in strategic preparedness for large scale evacuations. In doing so, while incorporating evacuation time considerations, we also take a cost perspective in designing an effective evacuation network. Both the network design and the associated cost considerations in evacuation planning are commonly ignored in the literature due to a focus on evacuation time and the associated flow routing objective.

We propose a mathematical model for Strategic Evacuation Network Design (SEND) that prescribes shelter regions and capacities, intermediate locations that support/supply for en route evacuees as well as road segments and their capacities under evacuation time constraints. To solve our model, we devise an efficient Benders Decomposition based approach enhanced with surrogate constraints, strengthened Benders cuts, heuristics, and the use of multi-cuts.

We apply our methodology to solve test instances developed based on real data from Central Texas. We demonstrate by our analysis that the resulting approach does not only provide us with a means to design evacuation networks but also serves as a tool to study the trade-offs involved in design and operational performance measures as it captures the essence of high-level interactions between them.

1. Introduction

Evacuation from extreme events is a complex and integrated operation that necessitates planning and cooperation from government officials at the local, state and federal levels, non-government entities for en route support of evacuees and evacuees themselves. Recent events that left a mark in terms of their response planning and execution as well as inadequacy of infrastructure and preparedness include Hurricane Katrina that hit the Southern coast of the United States with devastating effects in August 2005. 1800 people lost their lives and more than $81 billion in damages were incurred. Soon after in 2005, although its devastation was not as extensive as Katrina's, Hurricane Rita caused a mass evacuation that reminded

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strongly the lack of infrastructure and preparedness for such an event (Litman, 2006). In that case, almost 3.7 million people evacuated from a region between Beamont and Corpus Christi in coastal Texas, including Houston (Texas House of Representatives, 2006). More recently, the Hurricanes Harvey and Irma in 2017 once more reminded us the importance of being strategically prepared for such disasters.

Though there are several research articles and models which focus on hurricane and natural disaster evacuation, decidedly few are integrated into evacuation practice and the determination of evacuation policy. Instead, it remains the tradition of local and state law enforcement to issue a "mandatory evacuation" roughly 48 h prior to landfall (Lindell et al., 2011). The order to evacuate is not accompanied by any additional information and it is left largely to the general population to "fend for themselves" in determination of their actual evacuation time, route of egress, and final destination. In fact, the current published evacuation policy for the general population in the state of Texas suggests that evacuation to be largely self-directed and that evacuees be allowed to use any route out of coastal areas (Lindell et al., 2011). Interestingly, many people do not have a plan on where they are going to evacuate, what specific route they are going to take, etc.

The result is typically an immobile population faced with an impending hurricane and no means of escape to safety. One way to alleviate this strained population is to provide an evacuation strategy that is more directed while maintaining enough simplicity to be attractive. Instead of forcing the population to make their own evacuation plans, the offering of predetermined evacuation routes and sheltering locations is a viable alternative at least due to the fact that it provides the ability to plan the use of limited shared resources for the good of the population.

With this recognition, we emphasize that such decision making must be supported by an underlying evacuation network and resource capabilities that are *strategically determined* by also taking into account the mass flow of evacuees (which dictates the potential demand on the system). Therefore, in this paper, our main objective is to pose and analyze an evacuation network design problem in order to provide a strategic planning tool for emergency response planners. While incorporating evacuation time considerations as necessitated by the very nature of emergency planning, we also incorporate a cost perspective for the purpose of identifying an effective underlying evacuation network and we analyze the interplay between cost and evacuation time components in Strategic Evacuation Network Design. The cost perspective in evacuation planning is a commonly ignored dimension, however, it is important to consider this dimension as sound evacuation planning ultimately relies on the availability of resources that are not always freely and/or quickly available. To this end, we propose a mixed integer linear program, referred to as the Strategic Evacuation Network Design (SEND) model, to devise effective and controlled evacuation networks for sending evacuees from their origins to shelters during extreme events such as hurricanes. Specifically, given a potential large region (e.g., a metropolitan area with multiple counties) of evacuation, the SEND model provides an evacuation network design that identifies sheltering regions and their capacities, intermediate nodes (towns/main intersections along evacuation routes), and the road network to be utilized, including road segments and their capacities and evacuation routes from sources to shelter regions while satisfying road network capacity, shelter capacity, and evacuation time constraints with an overall objective to minimize total design and flow-related costs. The costs we consider are collectively faced by the decision makers ensuring safe evacuations. Being at a strategic level, our approach considers the evacuation of a large region, as illustrated in our case study, which is important on its own right as this was the need in the specific Hurricanes in the US mentioned above.

Furthermore, we develop an efficient solution methodology based on Benders Decomposition (BD) that can solve large scale instances of SEND within reasonable solution times and small optimality gaps. Our methodology shows outstanding performance compared with the branch-and-cut (via CPLEX) algorithm. We develop several performance enhancements including surrogate constraints, strengthened Benders cut generation, the generation of multiple Benders cuts, as well as efficient heuristics within the exact BD framework.

Finally, we conduct an experimental study to test our BD technique using data from Central Texas. We show that the SEND model can be utilized for efficient and effective strategic decision making while planning for large scale evacuations. Using the modeling and methodology developed in this study, we analyze the impact of input parameters on strategic design decisions for evacuation networks and clarify the trade-offs and relationships among important design characteristics including evacuation time, shelter and road selections and their capacities.

The remainder of this paper is organized as follows. Section 2 discusses relevant literature in the evacuation and general network design to better frame our contributions in both contexts. Section 3 describes the SEND problem and its assumptions, and provides notation and the model formulation. Section 4 describes a Benders Decomposition based approach for an efficient solution method to the SEND model. Computational results with input drawn from the state of Texas road network and evacuation resources data for Houston, TX are provided in Section 5. Finally, a summary and conclusions, including our current and future research in this area, are presented in Section 6.

2. Related literature

Studies on evacuation and extreme events are diverse, ranging from large-scale deterministic, regional evacuation models to small-scale simulations of building egress with varying objectives including minimization of evacuation time, maximization of the number of individuals evacuated, minimization of causalities, or some derivative thereof. The literature on evacuation analysis can also be extended to include a large number of post-event behavior surveys, e.g., Lindell et al. (2005); 2011), Wu et al. (2011) and Lindell et al. (2001), which attempt to describe evacuation performance with observed results. Before we continue with a comparative review of related studies for our purposes, we note that an extensive recent reviews