Proceedings of the 2025 Winter Simulation Conference
E. Azar, A. Djanatliev, A. Harper, C. Kogler, V. Ramamohan, A. Anagnostou, and S. J. E. Taylor, eds.

AN INTEGRATED OPTIMIZATION-SIMULATION FRAMEWORK FOR ZONE-BASED HURRICANE EVACUATION PLANNING

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ABSTRACT

We examine the partitioning of hurricane-affected regions into zones and the optimization of evacuation planning decisions for each zone under various hurricane scenarios, aiming to expedite evacuations and mitigate traffic congestion. We propose a framework that integrates a two-stage stochastic mixed-integer programming (SMIP) model and a simulation-based optimization model using a microscopic traffic simulator. The SMIP model provides a problem-specific initialization for the simulation-based optimization. Our experiments show that this hybrid framework balances computational tractability and model fidelity.

1 INTRODUCTION

Zone-based evacuation is a widely adopted strategy in emergency management, particularly for large-scale events such as hurricanes. In this strategy, regions impacted by hurricanes are divided into contiguous districts (i.e., zones). Operators then assign specific evacuation instructions to each zone based on the forecasted hurricane scenario and anticipated traffic conditions. Thus, the partitioning of zones serves to facilitate effective public communication, enabling residents to identify their zones and follow coordinated evacuation planning decisions.

Unlike previous research on evacuation planning optimization, we try not to make strong, unrealistic assumptions, e.g., that evacuees strictly adhere to operator instructions, such as prescribed departure times or mandatory routes. We instead assume that evacuees make independent decisions about when to leave and which routes to take and follow only basic government guidance, such as identifying their designated zone and complying with its evacuation deadlines. These assumptions are consistent with our motivation to establish zones: if everyone strictly followed centralized instructions without communication barriers, it would be unnecessary to divide regions into zones for high-level evacuation decisions.

Given the zones and evacuation deadlines, the evacuation process can be readily modeled through simulation, incorporating realistic human behavior. However, optimization is more challenging because the problem exhibits a two-stage structure: in the first stage, a districting plan must be determined, and in the second stage, optimal evacuation deadlines for each district must be identified for different hurricane scenarios. Moreover, the space of feasible districting plans that satisfy contiguity constraints is inherently difficult to search over.

2 METHODOLOGY AND RESULTS

2.1 Integrated optimization-simulation framework

Our solution approach is depicted in Figure 1. A two-stage stochastic mixed-integer programming (SMIP) model generates an initial districting plan under simplified assumptions, which informs and accelerates the simulation-based optimization model. The latter, in turn, refines the more simplistic SMIP model by capturing realistic human behavior. Additionally, when a specific districting plan and hurricane scenario

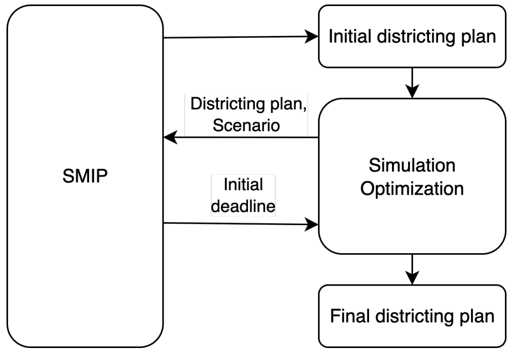

Figure 1: Integrated optimization-simulation framework.

are provided, the deadline solution from the SMIP model is used as the initial deadline within the second stage of the simulation-based optimization routine.

2.2 Two-stage SMIP model

We model hurricane uncertainty through a scenario tree and employ a two-stage SMIP model that utilizes the Cell Transmission Model of Daganzo (1994) to capture the dynamic behavior of traffic flow. The SMIP model finds an optimal districting plan and optimal evacuation deadlines for each source node under different hurricane scenarios. The SMIP model involves first-stage binary variables and second-stage mixed-integer programs (MIPs).

We propose a new branch-and-cut algorithm based on Progressive Hedging to solve the SMIP model. The main contributions of our proposed algorithm are twofold. First, we design a new branch-and-cut strategy and incorporate no-good cuts and minimal (a,b)-separator cuts. Second, we introduce a pattern pool mechanism to reduce the computational burden of solving the MIPs to completion. Through an illustrative case study, we validate our proposed algorithm's computational performance.

2.3 Simulation-based optimization model

We model the traffic network using a microscopic traffic simulator called SUMO and equip each vehicle with automatic rerouting capabilities to simulate realistic driving behavior.

Our simulation-based optimization approach involves a hierarchical local search. Specifically, we employ a stochastic hill-climbing algorithm to optimize the districting plan in the first stage and to optimize evacuation deadlines for a given districting plan in the second stage. Here, the SMIP model provides a problem-specific initialization in both stages of the hierarchical local search. Leveraging the SMIP model in this way enables the simulation optimization routine to start closer to high-quality areas of the search space, resulting in better solutions. The experimental results show that the initial districting plan obtained by SMIP ranks third among 20 randomly sampled districting plans in terms of solution quality, and subsequent simulation optimization from this initial districting plan yields the best known districting plan.

REFERENCES

Daganzo, C. F. 1994. "The Cell Transmission Model: A Dynamic Representation of Highway Traffic Consistent with the Hydrodynamic Theory". *Transportation Research Part B: Methodological* 28(4):269–287.