Towards Optimal and Scalable Evacuation Planning Using Data-driven Agent Based Models

Extended Abstract

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ABSTRACT

Evacuation planning is a crucial part of disaster management where the goal is to relocate people to safety and minimize casualties. Every evacuation plan has two essential components: routing and scheduling. However, joint optimization of these two components with objectives such as minimizing average evacuation time is a computationally hard problem. To approach it, we present MIP-LNS, a scalable optimization method that can optimize a variety of objective functions. We also present the method MIP-LNS-SIM, where we combine agent-based simulation with MIP-LNS to more accurately estimate delays on roads due to congestion. We use Harris County in Houston, Texas as our study area. We show that, within a given time limit, MIP-LNS finds better solutions than existing methods in terms of three different metrics. We also perform experiments with MIP-LNS-SIM to show its efficacy in estimating delays due to congestion. Our results show that, when such delays are considered, MIP-LNS-SIM can find better evacuation plans than MIP-LNS. Furthermore, MIP-LNS-SIM provides an estimate of the evacuation completion time for its plan with a small percent error.

KEYWORDS

Evacuation; Routing; Scheduling; Agent Based Simulation; NP-hard; Mixed Integer Program; Heuristic; Large Neighborhood Search

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1 INTRODUCTION

Evacuation plans are essential to ensure the safety of people living in areas that are prone to disasters such as floods, hurricanes, tsunamis and wildfires. Large-scale evacuations have been carried out during the past hurricane seasons in Florida, Texas, Louisiana, and Mississippi. To give a sense of the scale of these evacuations, about 6.5 million individuals were ordered to evacuate from the state of Florida [12] due to Hurricane Irma (2017). At such scale, it is essential to have an evacuation plan to ensure that people can evacuate safely. Any such plan needs to have two essential components: (*i*) Evacuation Routes, i.e. which roads to take, and (*ii*) Evacuation Schedule, i.e. when to leave. The goal is to find a plan that optimizes a desired objective such as average evacuation time, evacuation completion time. Jointly optimizing over the routes and schedule is computationally hard. Existing methods, even those designed to find bounded sub-optimal solutions (e.g. [2, 3, 10]), do not scale to city or county level planning problems. Moreover, most of the existing research works [2, 3, 5, 8, 10] do not consider the slowdown of traffic caused by large number of vehicles on the road.

Our contributions in this paper are as follows: **First**, we present MIP-LNS, a scalable optimization method that can find solutions to a class of evacuation planning (i.e. routing and scheduling) problems, while optimizing for a variety of objectives. **Second**, we use Harris County in Houston, Texas as our study area and show that within a given time limit, MIP-LNS finds better solutions than an existing baseline method [3] in terms of three different performance metrics. **Finally**, we present MIP-LNS-SIM, where we combine an agent-based simulation system QueST [7] with MIP-LNS to model delays caused by congestion in the road network. We show that MIP-LNS-SIM outperforms MIP-LNS when such delays are considered.

2 PROBLEM FORMULATION

To formulate the evacuation planning problem, we first introduce some preliminary terms. A *road network* is a directed graph where each edge e has a travel time (T_e) and a capacity (c_e) attribute. An *evacuation network* is a road network that specifies a set of source, safe and transit nodes. Each source node has a certain number of evacuees in it. A *single dynamic flow* is a flow along a single path where the flow takes T_e amount of time to travel on each edge e of the path. A *valid dynamic flow* is a collection of single dynamic flows where no edge at any point in time exceeds its edge capacity.

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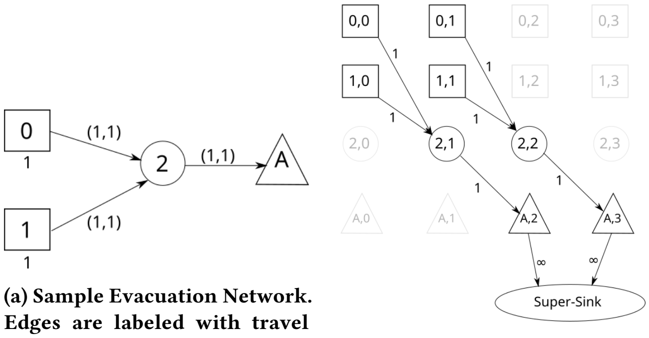

(a) Sample Evacuation Network. Edges are labeled with travel time and flow capacity respectively. Source, safe and transit nodes are denoted by squares, triangles, and circles respectively. Source nodes are labeled with number of evacuees.

(b) Time Expanded Graph (TEG) for the Sample Network. Edges are labeled with capacity. Construction of this TEG sets an upper bound of 3 time units for evacuation completion.

Figure 1: Sample Problem Instance

Given an evacuation network, we say a valid dynamic flow is an *evacuation schedule* if (i) all evacuees end up at some safe node, (ii) no single dynamic flow has any intermediary wait-time, and (iii) the underlying flow (without considering time) is confluent, where if two single dynamic flows use the same vertex (possibly at different times), their underlying path afterwards is identical. Formal definitions of these terms are provided in the technical report [6]. Let W denote the set of all evacuees and t_i denote the evacuation time of evacuee i. Then, we define the following planning problem:

Problem 1. *Average Dynamic Confluent Flow Problem (A-DCFP).* Given an *evacuation network*, let T_{max} represent an upper bound on evacuation time. Find an *evacuation schedule* such that all evacuees arrive at some safe node before time T_{max} while minimizing $\frac{1}{|W|}\sum_{i \in W} t_i$.

We also define two other planning problems (CT-DCFP, O-DCFP) with different objectives (details in [6]). To model the flow of evacuees over time we use *time-expanded graphs*. Here, we discretize the temporal domain into discrete timesteps and create copies of nodes and edges in the evacuation network at each timestep. A sample evacuation network and time-expanded graph is shown in Figure 1a–1b. We formulate all three planning problems as Mixed Integer Programs (provided in [6]).

3 METHODOLOGY

All three planning problems we consider in this paper are NP-hard to solve and NP-hard to approximate (proof in [6]). For this reason we present a scalable heuristic method **MIP-LNS** to quickly find solutions to these problems. MIP-LNS is designed based on the Large Neighborhood Search framework [9, 11] where we combine heuristic search with mathematical optimization. Here, we start with an initial feasible solution where we use shortest path routes (that are confluent) and the best schedule for these routes. We then explore the neighborhood of this solution by fixing some of the routes and optimizing over the rest. If we find a better solution in the process then we update our solution. We then continue to explore the neighborhood in search of better solutions and terminate after a certain number of iterations.

We also present the method **MIP-LNS-SIM** where we combine agent-based simulation with MIP-LNS. Specifically, to model the slowdown of traffic on roads due to congestion, we consider the travel time on roads as parameters to be learned. Initially, we assume that vehicles travel on the road at speed limit and calculate an evacuation plan based on this assumption using MIP-LNS. We then use QueST [7] to simulate the evacuation of a certain portion of the evacuees from each source. We look at the average travel time on the roads used in the plan and take it as an estimation of the travel time on these roads. Effectively, we utilize the simulator to learn the parameter values. We use these updated values to calculate a new evacuation plan and repeat the process. The process is terminated after a certain number of iterations. Pseudo-code of both MIP-LNS and MIP-LNS-SIM are provided in the technical report [6].

4 EXPERIMENTS

For our experiments, we use Harris County in Houston, Texas as our study area. We have used road-network data from HERE maps [4] and a synthetic population (as described by Adiga *et al.* [1]) to construct a realistic problem instance. To compare MIP-LNS with the baseline method (Benders Convergent (BC) method, proposed by Hasan and Van Hentenryck [3]), we applied both methods on our problem instance with a time limit. We then compared the solutions returned within the time limit. For A-DCFP, the evacuation plan found by MIP-LNS is on average 13%, 21%, and 58% better than the baseline solutions in terms of average evacuation time, evacuation completion time and optimality guarantee of the solution. We observed similar results for CT-DCFP and O-DCFP.

In the above experiment, we assumed that vehicles travel on edges at speed limit and calculated the travel time of the edges accordingly. However, during evacuations, the effective speed tends to be much lower due to the large number of vehicles on the roads. We designed MIP-LNS-SIM to capture this phenomenon. To investigate the effectiveness of MIP-LNS-SIM, compared to MIP-LNS, we used the evacuation plans from both of these methods to simulate the entire evacuation. Our results show that, when delays due to congestion is considered, MIP-LNS-SIM outperforms MIP-LNS in terms of evacuation completion time, average traffic density on the roads, and average time spent on the road by evacuees. Furthermore, MIP-LNS-SIM provides a more accurate estimate of the evacuation completion time for its plan than MIP-LNS. Detailed results are provided in the technical report [6].

5 CONCLUSION

In this paper, we have presented a general-purpose optimization method MIP-LNS to solve a class of evacuation planning problems. We demonstrated its efficacy by applying it on our study area of Harris county, Houston, Texas. We also designed the method MIP-LNS-SIM where we combined agent-based simulation with MIP-LNS to estimate delays caused by congestion. Through our experiments, we showed that MIP-LNS-SIM can find efficient evacuation plans and provide estimated evacuation completion time for its plans with small percent error.

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