Simulation Modelling Practice and Theory 67 (2016) 59–73

Contents lists available at ScienceDirect

Simulation Modelling Practice and Theory

journal homepage: www.elsevier.com/locate/simpat

Integration of simulation and optimization for evacuation planning

Heng-Soon Gan [a], Kai-Florian Richter [b,*], Mingzheng Shi [c], Stephan Winter [d]

[a] Department of Mathematics and Statistics, The University of Melbourne, Parkville 3010 VIC, Australia
[b] Department of Geography, University of Zurich, Winterthurerstrasse 190, Zurich 8057, Switzerland
[c] Centre for Technology Infusion, La Trobe University, 2 Research Ave, Bundoora 3086 VIC, Australia
[d] Department of Infrastructure Engineering, The University of Melbourne, Parkville 3010 VIC, Australia

ARTICLE INFO

Article history:
Received 30 November 2015
Revised 22 April 2016
Accepted 1 July 2016

Keywords:
Disaster management
Evacuation modeling
Optimization
Traffic micro-simulation
Mixed integer programing

ABSTRACT

Evacuation is a time critical process in which the highest priority is to get those people who may be affected by a disaster out of the danger zone as fast as possible. For disaster-prone areas, authorities often distribute evacuation plans well in advance, or encourage the population to prepare themselves for eventual disasters. This paper presents an approach to such planning ahead for evacuation that tightly couples optimization and traffic simulation in order to determine optimal evacuation time and exit from the area for each evacuee. In this paper, we discuss the approach's properties and illustrate its performance using two case studies of wildfire-prone areas in the state of Victoria, Australia. The results show that our approach can lead to significant improvements when compared to ad-hoc evacuation, but these improvements also strongly depend on population density and road network topology. More generally, our research highlights the significant benefits of tightly coupling optimization and simulation for evacuation modeling.

1. Introduction

Evacuation is a time critical process. When a disaster is imminent or has already struck, getting people out of the danger zone as quickly as possible usually has highest priority. Such evacuation may pose a major challenge, depending among others on how infrastructure is affected by the disaster, the characteristics of the environment, and the level of preparedness of evacuees and authorities.

Chiu et al. [1] distinguish two situations: (1) no-notice disasters, i.e., disasters where no advance notice can be issued (e.g., an explosion, an earthquake, or a terrorist attack); (2) short-notice disasters, i.e., cases where it is known at least a few hours to several days in advance that a disaster is about to strike (e.g., a hurricane, flooding, or most bush or forest fires). In the former, intervention by authorities is obviously much harder, as there is no preparation time and people may begin to evacuate the affected regions before authorities have an overview of the situation. The latter allows for some preparation and potentially more ordered evacuation procedures. In both cases, it is possible to follow implemented evacuation plans in principle. People may take pre-planned routes and/or try to reach dedicated safe zones. In this paper, we are only interested in the latter case, i.e., disasters whose occurrence is known (well) in advance.

* Corresponding author. Tel.: +41 44 635 51 52.
E-mail addresses: hsg@unimelb.edu.au (H.-S. Gan), kfr@kfrichter.org (K.-F. Richter), m.shi@latrobe.edu.au (M. Shi), winter@unimelb.edu.au (S. Winter).

http://dx.doi.org/10.1016/j.simpat.2016.07.001
1569-190X/

Still, the problem of evacuating a region at risk as fast as possible is often plagued by traffic congestion, especially in areas where the road network density is low (e.g., [2]). Congestions can be dealt with at two levels, namely the planning phase and in real time, i.e., during the actual evacuation. In this paper, we will primarily focus on alleviating the evacuation congestion issues in the planning phase, via staged evacuation and exit assignment. More specifically, we would like to determine, for each evacuee in the region at risk, the exit to take (with a pre-determined path choice) and their departure time. These optimized departure times and exit assignments are intended to be used as a fixed instruction to the local residents of a region at risk, since giving real-time instructions can be very challenging during a disaster event.

Our approach integrates optimization and simulation procedures to find optimal instruction sets for the evacuees. The mixed-integer linear program optimization finds parameter settings of path choice and departure time for every evacuee. However, the parameter settings are only optimal under the simplified assumptions necessarily underlying such optimization, most importantly its essentially static view on the evacuation process. Thus, we feed these parameter settings into a traffic simulator and run a simulated evacuation that also accounts for dynamic aspects. These dynamic aspects include, among others, variations in travel speed between different cars as well as during a single car's travel, and overall depict individual driving behavior and collective dynamics of traffic flow in a realistic way. The results of the simulation are then fed back into the optimization in a tightly coupled iterative process leading to better informed new parameter settings. This tight coupling provides a more realistic picture of what would actually happen if a disaster struck and, thus, allows for better informed decisions in planning for evacuation. The close coupling of optimization and simulation is the major contribution of this paper.

The paper is structured as follows. The next section discusses prior research in the area of evacuation management, specifically, evacuation simulation using agent-based modeling, optimization of network flow, and optimization for evacuation plans. Section 3 then discusses our approach of tightly coupling optimization and simulation in more detail. The traffic simulator iWays used in our approach is introduced in Section 4, and Section 5 further motivates the effectiveness of our approach. Settings and results of two case studies are presented in Section 6, followed by a discussion of these results and outlook on future work in Section 7.

2. Planning and optimization for evacuation

Any disaster management plan encompasses some evacuation management, i.e., the guidance of large numbers of people out of a zone of danger. The overarching question in any such management is how to get as many – ideally all – people out of the danger zone as quickly and safely as possible. Different approaches to this challenge have been pursued in research over the years; broadly distinguished in simulation and optimization approaches.

For the modeling of evacuation processes, agent-based simulation is an accepted methodology (e.g., [3–5]). Such simulations aim at establishing required evacuation times. They usually also investigate how specific aspects of the evacuation process and changes to these aspects influence evacuation behavior and times. For example, there has been work on investigating the influence of environments on evacuation processes [4,6], effects of individual behavior on the network flow [7], or the simulation of human behavior in disaster situations [5,8].

Kim et al. [9] suggested reconfiguring a transportation network by reversing lane directions. In their simulations, they compare different heuristics for solving this contraflow problem. Reversing lanes clearly increases the network's flow capacity. However, it is important to note that contraflow lanes are mostly only applicable for highways or major arteries in cities; for many rural areas streets are simply not wide enough for such an approach to have a significant effect, or even to be safely applicable. Without changing the network's structure, Daganzo and So [10] also aimed for increasing network flow by managing the network's core such that on these parts no congestions occur. Their approach is decentralized, i.e., each entry can be managed locally, and their strategy is proven to be optimal. However, traffic on the back roads remains uncontrolled and managing merging traffic at the entries requires some infrastructure and likelyeven law enforcement personnel to ensure that people adhere to the signaling in cases of emergency and stress.

Lu et al. [11] introduced a capacity constraint route planner, which aims for both minimizing evacuation time and the compute time needed to come up with an evacuation plan. Their approach uses a centralized view, i.e., a planning authority knows about the complete state of the network evacuation happens in. According to the authors this approach is more scalable than linear programing, however, not guaranteed to find an optimal solution as it uses a heuristic approximation (see also [12]).

Next to an environment's properties people's behavior is of major interest. Based on how early before a wildfire will reach their area people will leave, Beloglazov et al. [8] categorized people into different groups. According to the behavior categorization, different parties will leave an area at different times; in this simulation they will always leave for the nearest safe destination. Running a traffic simulation the authors compare their dynamic model with a static case, where departure times follow some global distribution. They observe clear differences in clearance time for most regions between the two scenarios. Usually, the dynamic model leads to faster overall evacuation of a region, particularly for those regions closer to the fire ignition points. But regions farther away often take longer to evacuate in the dynamic case, because by the time people there start leaving there is already considerable traffic on the roads.

Chen and colleagues [3,13] explored the emergence of bottlenecks and congestions, which happen when a lot of evacuees try to escape at the same time, by comparing simultaneous and staged evacuation strategies. Using agent-based simulations run on different kinds of networks, Chen et al. compared the different evacuation strategies by exhaustingly assigning each