ECAI 2014
T. Schaub et al. (Eds.)

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doi:10.3233/978-1-61499-419-0-1143

NICTA Evacuation Planner: Actionable Evacuation Plans with Contraflows

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Abstract. Evacuations are a critical aspect of disaster management, and generally the first prevention measure to ensure the safety of the population under threat. Designing evacuation plans is a complex task that requires to take into account multiple factors in order to limit congestion and ensure that all evacuees reach safety in time. This paper proposes a conflict-based path-generation algorithm for evacuation planning and a web-based intelligent system targeted at local authorities and emergency services. The key contribution of this paper is to propose the first scalable approach to produce actionable evacuation plans that simultaneously schedules the evacuation and selects contraflow roads. The benefits of the approach are illustrated on two large-scale case studies. The resulting optimization model is integrated in NICTA EVACUATION PLANNER, a tool to model, plan, and simulate evacuations.

1 INTRODUCTION

Evacuation orders are arguably the most important decision enforced by local authorities to ensure the safety of a population under a major threat. Depending on the threat, the affected area can vary from a building (e.g., in the case of a fire), to a neighborhood (e.g., in the case of an industrial hazard) and a large regional area (e.g., in the case of a hurricane). In areas prone to natural disasters or in the vicinity of industrial hazards, evacuation plans are generally designed beforehand and enforced whenever a threat arises. However, this process generally relies on expert knowledge and is performed manually. A direct consequence is that local authorities cannot always react to unforeseen threats or to changing conditions during the execution of the evacuation. This stresses the need for intelligent evacuation planning systems that embody the practice in the field and take advantage of state-of-the-art artificial intelligence and operations research techniques to produce high-quality plans in real time.

The critical challenge for evacuation planning is how to deal with congestion since the capacity of the road network is the main limitation for regional evacuations using personal vehicles. Congestion can rapidly propagate in the network, preventing people from evacuating and increasing the risk for evacuees of being trapped in the affected areas.

A first strategy to reduce congestion is to prepare evacuation plans minimizing the conflicts between evacuated areas. The key is to choose evacuation paths and to stage the evacuation to distribute the pressure on the road network evenly. The authors addressed this challenge for large scale evacuation plans with a Conflict-Based Path-Generation Heuristic (CPG) [14].

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A second strategy aims at increasing the capacity of the road network by reversing the direction of certain lanes on major roads. This procedure, known as contraflows [12], is implemented on a regular basis for large-scale evacuations such as the evacuation of New Orleans in preparation for hurricane Katrina in 2005. Contraflows can virtually double the capacity of the selected roads without affecting traffic safety [12]. However, contraflows also increase the complexity of evacuation planning by adding a new degree of freedom: Selecting roads that will be used in contraflows is $\mathcal{NP}$-Hard [8]. Additionally, contraflows have an operational cost as they require specific traffic control measures.

This work combines these two strategies. It proposes the first scalable and comprehensive approach to simultaneously design an evacuation plan and decide which roads should be used in contraflows. The experimental results show that it is computationally possible to plan effective, large-scale evacuations with contraflows for threat scenarios involving up to 1,000,000 people. The approach can also be adapted to other contexts such as building or pedestrian evacuations.

The remainder of this paper is organized as follows: Section 2 formally defines the evacuation planning problem; Section 3 briefly reviews the literature on evacuation planning and contraflows; Section 4 details the proposed approach and Section 5 presents a web-based intelligent evacuation planning system; Section 6 presents a computational results on two case studies. Finally, Section 7 draws conclusions and directions for future research.

2 Problem Formulation

Figure 1 illustrates an instance of the Evacuation Planning Problem (EPP) as introduced by the authors in previous work [14]. Figure 1(a) presents an evacuation scenario with one evacuated node (0) and two safe nodes (A and B). In this example, the evacuated node 0 has to be evacuated by 13:00, considering that certain links become unavailable at different times (for instance, $(2, 3)$ is cut at 9:00). This evacuation scenario can be represented by the graph $\mathcal{G} = (\mathcal{N} = \mathcal{E} \cup \mathcal{T} \cup \mathcal{S}, \mathcal{A})$ of Figure 1(b), where $\mathcal{E}$, $\mathcal{T}$, and $\mathcal{S}$ are the set of evacuated, transit, and safe nodes respectively, and $\mathcal{A}$ is the set of directed edges. Each evacuated node i is characterized by a number of evacuees d_i and an evacuation deadline f_i (e.g., 20 and 13:00 for node 0 respectively), while each edge e is associated with a triple (s_e, u_e, f_e), where s_e is the travel time, u_e is the capacity, and f_e is the time at which the edge becomes unavailable. Finally, we note $\mathcal{A}_c \subseteq \mathcal{A}$ the subset of edges that can be used in contraflow. In practice, $\mathcal{A}_c$ will contain major roads and one-way streets.

A common way to deal with the space-time aspects of evacuation problems is to discretize the planning horizon into time steps of identical length, and to work on a *time-expanded graph*, as illustrated in Figure 2. This graph $\mathcal{G}^d = (\mathcal{N}^d = \mathcal{E}^d \cup \mathcal{T}^d \cup \mathcal{S}^d, \mathcal{A}^d)$ is constructed

(a) Evacuation Scenario (b) Evacuation Graph

Figure 1. Modeling of an Evacuation Planning Problem.

by duplicating each node from $\mathcal{N}$ for each time step. For each edge $(i, j) \in \mathcal{A}$ and for each time step t in which edge (i, j) is available, an edge$(i_t, j_{t+s_{(i,j)}})$ is created to model the transfer of evacuees from node i at time t to node j at time $t + s_{(i,j)}$. In addition, edges with infinite capacity are added to model evacuees waiting at evacuated and safe nodes. Finally, all evacuated nodes (resp. safe nodes) are connected to a virtual super-source v_s (super-sink v_t), modeling the inflow (outflow) of evacuees. Note that some nodes may not be connected to either the super-source or super-sink (in light gray in this example), and can therefore be removed to reduce the graph size. The problem is then to find a flow from v_s to v_t that models the movements of evacuees in space and time.

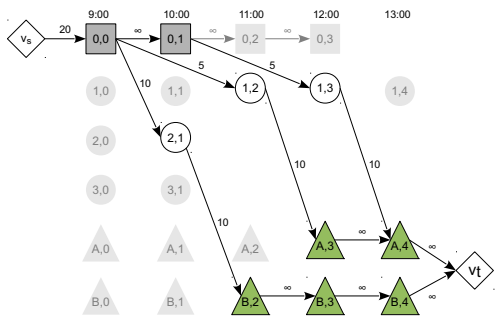

Figure 2. An example of a time-expanded graph for the evacuation scenario with 1-hour time steps.

This study assumes that a single threat scenario is known at decision time and that a planner instructs each evacuee when to leave, which safe node to go to, and which path to follow. For practical reasons, all the evacuees from a same node are instructed to follow the same path. (These assumptions are consistent with evacuation and mobilization practices in Australia.) The problem is then to design an evacuation plan that assigns a single evacuation path to each evacuated node, and to schedule the evacuation over the planning horizon, with the objective of first maximizing the number of evacuees reaching a safe node, and then minimizing the time at which the last evacuee reaches safety. Edge capacities are chosen conservatively to ensure a constant speed and avoid congestion at intersections.

3 Related Work

In practice, contraflows have been enforced in a number of large-scale evacuations, and have therefore received significant attention from practitioners. Wolshon [16] presents a history of contraflow implementations, lists their operational characteristics, and provides practical details. The author reveals major issues faced in past events such as the evacuation of the New Orleans during hurricane Katrina and draws recommendations for future situations, highlighting the benefits of contraflows in properly monitored evacuations. An extensive review of operational aspects of evacuations can be found in the study by Murray-Tuite and Wolshon [13].

Despite its practical importance, evacuation planning has received only limited interest from the research community. As defined by Hamacher and Tjandra [4], evacuation planning can be tackled using either *microscopic* or *macroscopic* approaches. Microscopic approaches focus on modeling and simulating the evacuees individual behaviors, movements, and interactions. Macroscopic approaches, such as the one presented in this study, aggregate evacuees and model their movements as a flow in the evacuation graph.

To the best of our knowledge, only a handful of studies attempt to design evacuation plans as we defined them. Huibregtse et al. [7] propose a two-stage algorithm that first generates a set of evacuation routes and feasible departure times, and then assigns a route and time to each evacuated area using an ant colony optimization algorithm. A key feature of the approach is the use of traffic simulation to evaluate the quality of solutions. In later work, the authors studied the robustness of the produced solution [6], and strategies to improve the compliance of evacuees [5].

A significant number of contributions attempt to solve flow problems directly derived from the time-expanded graph. For instance, Lu et al. [11] propose three heuristics to design an evacuation plan with multiple evacuation routes per evacuated node, minimizing the time of the last evacuation. Liu et al. [10] propose a Heuristic Algorithm for Staged Traffic Evacuation (HASTE) that generates augmenting chains in the time-expanded graph. The main difference between HASTE and earlier algorithms is its reliance on a Cell Transmission Model (CTM)[3] to model more accurately the flow of evacuees. Lim et al. [9] consider a short-notice regional evacuation maximizing the number of evacuees reaching safety weighted by the severity of the threat and propose two solution approaches. Other authors have focused on modeling more accurately the transportation network. For example, Bretschneider and Kimms[2] present a free-flow mathematical model that describes in detail the street network and, in particular, the lane configuration at intersections of the network. Bish and Sherali [1] present a model based on a CTM that assigns a single evacuation path to each evacuated node. Microscopic approaches include the work by Richter et al. [15] who propose a decentralized decision making approach supported by smartphones and mobile applications.

Contraflow strategies have been studied in the context of free-flow models. Kim et al. [8] present a macroscopic optimization model that finds a contraflow network configuration such that the total evacuation time is minimized. The authors separate the contraflow network reconfiguration model, which decides which roads will be used in contraflow, from the route planner, which gives information on the flow of vehicles and is treated as a black box. They propose three approaches depending on the ratio of the number of evacuees over the network capacity (measure as its min-cut value), referred to as overload. The authors propose an Integer Program (IP) for low overload, and two greedy heuristics for medium and high overload. They compare the performance of three route planners from the literature. The main limitation of their approach is the fact the IP formulation becomes infeasible if not all evacuees can be evacuated. Xie and Turnquist [17] present a detailed model of lane configuration for road segments and intersections, which includes contraflow strategies. They propose an integrated Lagrangian and tabu search

approach that decides the lane configuration at each intersection to avoid crossings and maximize flow. However, the method does not produce evacuation plans for each evacuated zone.

Contrary to existing approaches, the algorithm in this paper is the first to combine *actionable evacuation plans*, which provide an evacuation path and departure time to each evacuee, *evacuation staging*, which distributes the load on the network over time, and *contraflow selection* for roads. In addition, the optimization models are integrated in the NICTA EVACUATION PLANNER, a web-based intelligent system for evacuation. The result is an integrated tool that provides a wide array of functionalities to evacuation planners and produces high-quality evacuation plans.

4 Proposed Approaches

This paper proposes a Conflict-Based Heuristic Path Generation approach (CPG) that separates the generation of evacuation paths from the scheduling of the evacuation. Algorithm 1 gives an overview of the CPG approach. First, the algorithm generates an initial set of paths Ω' (line 1) and solves a master scheduling problem to find an evacuation schedule optimizing the objective function (line 2). Then it identifies *critical* evacuated nodes $\mathcal{E}_c$ (line 4), which are not fully evacuated or evacuated late, and includes nodes that are potentially in conflict. In the next step, the algorithm generates new paths for the nodes in $\mathcal{E}_c$ (line 5). Finally, it solves the scheduling problem including the newly generated paths (line 6). The steps (4-6) are repeated until a stopping criterion is met (line 3).

Algorithm 1 The Conflict-Based Path Generation.

HN-Input: $\mathcal{G}$ the evacuation graph, $\mathcal{G}^d$ the time-expanded graph.
Output: $\mathcal{S}$ the best solution found
1: $\Omega' \leftarrow$ `generatePaths` $(\mathcal{G}, \emptyset, \mathcal{E}, \emptyset)$
2: $\mathcal{S} \leftarrow$ `scheduleEvacuation` $\left(\Omega', \mathcal{G}, \mathcal{G}^d\right)$
3: **while** stopping criterion not met **do**
4: $\quad \mathcal{E}_c \leftarrow$ `findCriticalEvacuatedNodes` $(\mathcal{S})$
5: $\quad \Omega' \leftarrow \Omega' \cup$ `generatePaths` $(\mathcal{G}, \Omega', \mathcal{E}_c, \mathcal{S})$
6: $\quad \mathcal{S} \leftarrow$ `scheduleEvacuation` $\left(\Omega', \mathcal{G}, \mathcal{G}^d\right)$
7: **end while**
8: **return** $\mathcal{S}$

Both the original (CPG) and contraflow (CPC-CF) approaches rely on the structure described in Algorithm 1. They share the same path generation procedure, but have different master scheduling problems, referred to as CPG-MP and CPG-CF-MP respectively.

4.1 Path Generation

The Path Generation (PG) algorithm aims at generating evacuation paths that improve the solution of the master problem MP. As explained in the next section, the structure of the MP does not allow for traditional column generation approaches. Therefore, the algorithm exploits a randomized heuristic that uses costs derived from the incumbent solution to the MP in order to generate new paths.

The approach finds, for each node from $\mathcal{E}_c$, the shortest path to any safe node in the evacuation graph $\mathcal{G}$. In other words, it transforms a multi-commodity flow problem in the time-expanded graph into a series of shortest paths in the evacuation graph, relaxing the edge-capacity constraints in the form of a penalty in the objective function. More specifically, the cost c_e of edge e is adjusted at each iteration using the linear combination of the edge travel time s_e, the number of occurrences of e in the current set of paths Ω', and the utilization of e in the incumbent solution:

$$c_e = \alpha_t \frac{s_e}{\max_{e \in \mathcal{E}} s_e} + \alpha_c \frac{\sum_{\substack{p \in \Omega' \\ e \in p}} 1}{|\Omega'|} + \alpha_u \frac{\sum_{\substack{p \in \Omega' \\ e \in p}} \sum_{t \in \mathcal{H}_p} \varphi_p^t}{u_e} \quad (1)$$

where α_t, α_c, and α_u are positive weights summing to 1.

4.2 CPG-MP

The master problem of the orginal algorithm (CPG-MP) is responsible for the assignment of evacuation paths to evacuated nodes, and the scheduling of the evacuation over the horizon.

Let Ω be a set of feasible paths between evacuated nodes and safe nodes, and Ω_k the subset of evacuation paths for evacuated node k. We define a binary variable x_p which takes the value of 1 if and only if path $p \in \Omega$ is selected, a continuous variable φ_p^t representing the number of evacuees that leave on path p at time t, and a continuous variable φ_k accounting for the number of non-evacuated evacuees in node k. In addition, we denote by $\omega(e)$ the subset of paths that contain edge e, and by τ_p^e the number of time steps required to reach edge e when following path p. Finally, we note $\mathcal{H}_p \subseteq \mathcal{H}$ the subset of time steps in which path p is usable, and u_p the capacity of path p, defined as the maximum flow on path p over $\mathcal{H}$.

$$\min \quad \sum_{k \in \mathcal{E}} \varphi_k c_e + \sum_{p \in \Omega} \sum_{t \in \mathcal{H}_p} \varphi_p^t c_p^t \quad (2)$$

$$\text{s.t.} \quad \sum_{p \in \Omega_k} x_p = 1 \qquad \forall k \in \mathcal{E} \quad (3)$$

$$\sum_{p \in \Omega_k} \sum_{t \in \mathcal{H}_p} \varphi_p^t + \varphi_k = d_k \qquad \forall k \in \mathcal{E} \quad (4)$$

$$\sum_{\substack{p \in \omega(e) \\ t - \tau_p^e \in \mathcal{H}_p}} \varphi_p^{t-\tau_p^e} \leq u_e \qquad \forall e \in \mathcal{A}, t \in \mathcal{H} \quad (5)$$

$$\sum_{t \in \mathcal{H}_p} \varphi_p^t \leq |\mathcal{H}_p| x_p u_p \qquad \forall p \in \Omega \quad (6)$$

$$\varphi_p^t \geq 0 \qquad \forall p \in \Omega, t \in \mathcal{H}_p \quad (7)$$

$$\varphi_k \geq 0 \qquad \forall k \in \mathcal{E} \quad (8)$$

$$x_p \in \{0, 1\} \qquad \forall p \in \Omega \quad (9)$$

Model (2-9) presents the master scheduling problem CPG-MP. The objective (2) minimizes the cost of the solution as defined previously. Constraints (3) ensure that exactly one path is selected for each evacuated node, while constraints (4) account for the number of evacuated and non-evacuated evacuees. Constraints (5) enforce the capacity on the edges of the graph. Finally, constraints (6) ensure that there is no flow on paths that are not selected.

Figure 3 highlights a specificity of the MP model: each new path p^* adds a binary variable x_{p^*}, a set of continuous variables $\varphi_{p^*}^t$, and a set of constraints (6). For this reason, traditional column generation approaches cannot be used to generate new paths. It is worth noting that the master problem does not use a variable for each edge e and time step t, but relies on variables φ_p^t. This greatly reduces the number of variables, and changes the structure of the MP.

4.3 CPG-CF-MP

Like in CPG-MP, the contraflow master scheduling Problem (CPG-CF-MP) assigns paths to evacuated nodes, and then schedules the

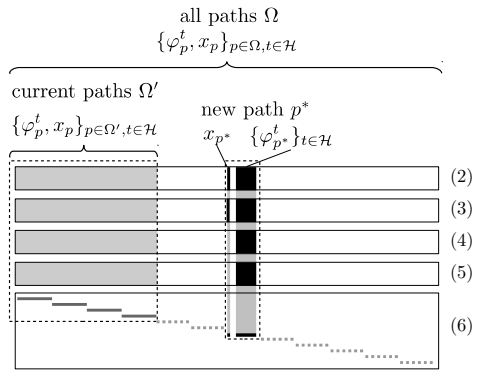

Figure 3. The structure of the MP model.

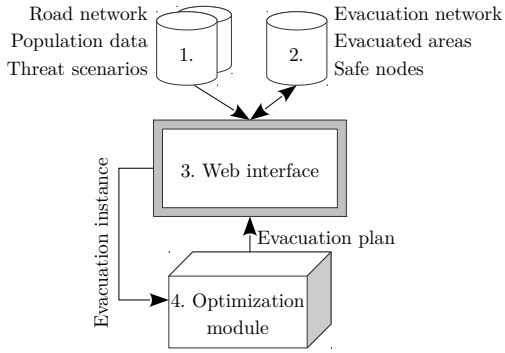

Figure 4. The Web Interface of the NICTA Evacuation Planner.

evacuation. However, the two models differ in the way the edge capacity is modeled.

Considering that the evacuation graph is directed and contains at most one edge between two nodes in each direction, we define $\bar{e}$ as the unique edge going in the opposite direction of edge $e \in \mathcal{A}_c$. In addition, we define an arbitrary partition $\mathcal{A}_c = \{\hat{\mathcal{A}}_c | \check{\mathcal{A}}_c\}$ such that $\forall e \in \hat{\mathcal{A}}_c, \bar{e} \in \check{\mathcal{A}}_c$. In order to control the contraflows, we create a binary variable x_e for edge $e \in \mathcal{A}_c$ equal to 1 if edge e is used in its normal direction. With this definition, there are three possible configuration $(x_e, x_{\bar{e}})$ for a road segment $(e, \bar{e})$: $(1, 1)$ if both edges are used in their normal direction, $(1, 0)$ if edge $\bar{e}$ is in contraflow, $(0, 1)$ if edge e is in contraflow.

$$\min \quad \sum_{k\in\mathcal{E}} \varphi_k c_{ne} + \sum_{p\in\Omega} \sum_{t\in\mathcal{H}_p} \varphi_p^t c_p^t \tag{10}$$

s.t.

$$\sum_{p\in\Omega_k} x_p = 1 \qquad \forall k \in \mathcal{E} \tag{11}$$

$$\sum_{p\in\Omega_k} \sum_{t\in\mathcal{H}_p} \varphi_p^t + \varphi_k = d_k \qquad \forall k \in \mathcal{E} \tag{12}$$

$$\sum_{\substack{p\in\omega(e)\\ t-\tau_p^e\in\mathcal{H}_p}} \varphi_p^{t-\tau_p^e} \le u_e \qquad \forall e \in \mathcal{A}\setminus\mathcal{A}_c, t \in \mathcal{H} \tag{13}$$

$$\sum_{t\in\mathcal{H}_p} \varphi_p^t \le |\mathcal{H}_p| x_p u_p \qquad \forall p \in \Omega \tag{14}$$

$$\sum_{\substack{p\in\omega(e)\\ t-\tau_p^e\in\mathcal{H}_p}} \varphi_p^{t-\tau_p^e} \le x_e u_e + (1-x_{\bar{e}})u_{\bar{e}} \qquad e \in \mathcal{A}_c, t \in \mathcal{H} \tag{15}$$

$$x_e + x_{\bar{e}} \ge 1 \qquad \forall e \in \hat{\mathcal{A}}_c \tag{16}$$

$$x_e \ge x_p \qquad \forall e \in \mathcal{A}_c, \forall p \in \omega(e) \tag{17}$$

$$x_p \in \{0,1\}, \varphi_p^t, \varphi_k \ge 0 \qquad \forall p \in \Omega, k \in \mathcal{E}, t \in \mathcal{H}_p \tag{18}$$

Model (10-18) details the contraflow master scheduling problem CPG-CF-MP. Constraints (11-13) are identical to (3-5) in CPG-MP. Constraints (15) enforce the capacity on edges that allow contraflow. They allocates to e the capacity of edge $\bar{e}$ whenever $\bar{e}$ is used in contraflow, and forbid any flow on e when it is used in contraflow. Constraints (16) prohibit the simultaneous use of e and $\bar{e}$ in contraflow. Finally constraints (17) force the use of the edges in any selected path.

In this model, the contraflows and their directions remain the same for the entire evacuation. In theory, changing the sense of contraflows could be useful when evacuating an area threatened by a disaster with unpredictable expansion. Bushfires, for instance, are highly dependent on wind conditions and a variation in wind direction may change the direction of the fire without notice. In practice though, contraflows require significant coordination efforts and it does not appear desirable to change the direction of lanes over time.

The set of edges allowing contraflow $\mathcal{A}_c$ is decided prior to computation. Based on the consideration that authorities in charge of the evacuation can monitor contraflow lane reversals only on a few portions of roads, we decided to allow contraflow on the road sections that are the most likely to make the evacuation quicker. Those roads are usually main roads such as highways and freeways with a great capacity and a shorter travel time. Beyond the fact that it is not practical to implement contraflow on every road section due to a limited number of resources, the benefit of using contraflows on secondary roads is rather limited as they have a lower contribution to the network outflow capacity. In fact, the major roads are usually the bottlenecks as they collect traffic from a number of evacuated areas to specific safe zones.

5 NICTA Evacuation Planner

Figure 4 presents an overview of the NICTA EVACUATION PLANNER, an intelligent system for integrated evacuation planning. In a nutshell, the tool pulls information from raw databases (1) containing the detailed road network (e.g., via Open Street Maps), population census, threat scenarios, and preprocesses the data to display it to the planners via the web interface (3). Planners are able to manipulate the data and define the evacuation network (which can be a simplified or reduced version of the road network). Planners can then specify the areas that need to be evacuated, as well as the safe areas and shelters. This information is saved in a database (2) and can be combined to produce an evacuation instance which is then used as input to the evacuation optimization module (4). The resulting evacuation plans are then presented to the planner who can then iterate the process, refining the selection of residential zones, evacuation roads, contraflow edges, and threat scenarios.

The web interface presented in Figure 5 allows planners to work with multiple scenarios simultaneously. The left panel presents the

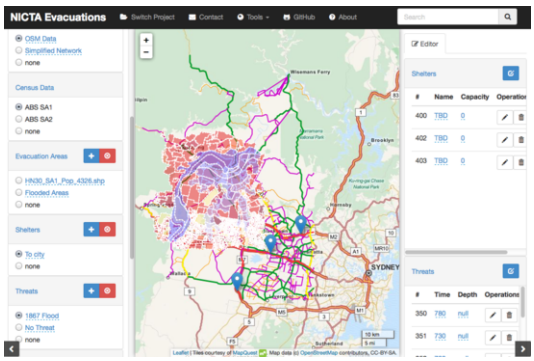

Figure 5. The NICTA Evacuation Planner web interface.

different layers (e.g., road network, population, evacuated areas), while the right panel provides editing functionalities.

6 Computational Experiments

This section considers two case studies to assess the quality and performance of our algorithms. The first is the Hawkesbury-Nepean (HN) floodplain, located North-West of Sydney, for which a 1-in-200 years flood would require the evacuation of 70,000 persons (approximately 38,000 vehicles). The evacuation graph contains 80 evacuated nodes, 6 safe nodes, 191 transit nodes, and 604 edges. The algorithms consider a time horizon of 10 hours with a time step of 5 minutes (starting at 00h00). The HN-Ix instances share the same evacuation graph but the number of evacuees is scaled by a factor of $x \in [1.1, 3.0]$. The second is the New Orleans Metropolitan Area (NO), which is threatened by hurricanes of category 2 or more every 3 years on average. Stronger hurricanes such as Katrina in 2005 require the evacuation of more than 1 million people (approximately 400,000 vehicles). The evacuation graph in this case study contains 323 evacuated nodes, 5 safe nodes, 1493 transit nodes, and 3606 edges. The algorithms consider a time horizon of 72 hours divided in time steps of 20 minutes.

All approaches were implemented using Java 7 and GUROBI 5.5. Experiments were conducted on a cluster of 64bits machines with 2.8GHz AMD 6-Core Opteron 4184 and 16Gb of RAM. The path generation method relies on Dijsktra's algorithm to compute the shortest paths. Both CPG and CPG-CF have a limit of 10 iterations.

Table 1 presents the number of paths generated (Num. Paths), the numbers of variables (Num. Cols) and constraints (Num. Rows) of the MP model, the total computational time (CPU Time), the percentage of evacuees reaching safety (Perc. Evac.), and the time required to complete the evacuation (Evac. Time) for CPG and CPG-CF on the HN-Ix instances. Results are an average over 10 runs given the randomized nature of the algorithms. The results illustrate the benefits of using contraflows both in terms of the percentage of people evacuated and the total evacuation time. It only takes 5 hours and 34 minutes to evacuate the population for the whole Hawkesbury-Nepean region with CPG-CF compared to a total evacuation time of 8 hours for CPG. In addition, CPG-CF is able to evacuate 91% of vehicles in the HN region in 10 hours when the population is increased by 200%, whereas CPG only evacuates 72% of the vehicles. The total number of paths generated is consistent across instances, with an average of 1,066 paths, which correspond to 100 paths per iteration. The variance is explained by the generation of duplicate paths that are discarded. The results also indicate that the numbers of columns and rows vary with the instance. This is due to the fact that we use the incumbent solution to discard variables that would lead to a longer evacuation time. Therefore the size of the MP decreases with the evacuation time in the incumbent solution. The CPG-CF model consistently evacuates more persons in less time, which in turns translate into fewer columns and rows in the model, and average computational times lower than CPG, despite a larger number of binary variables a priori.

Solver	Instance	Num. Paths	Num. Cols (10^3)	Num. Rows (10^3)	CPU Time (min)	Perc. Evac.	Evac. Time
CPG	**HN**	1014	78	54	15	100%	08h05
	HN-I1.1	1050	88	54	19	100%	08h45
	HN-I1.2	1090	101	54	18	100%	09h25
	HN-I1.4	735	73	54	6	99%	10h00
	HN-I1.7	1160	116	54	30	97%	10h00
	HN-I2.0	983	99	54	30	91%	10h00
	HN-I2.5	1046	106	54	36	80%	10h00
	HN-I3.0	958	96	54	32	72%	10h00
CPG-CF	**HN**	1125	47	74	6	100%	05h34
	HN-I1.1	1183	56	75	10	100%	06h00
	HN-I1.2	1248	62	76	12	100%	06h14
	HN-I1.4	1055	68	72	15	100%	07h17
	HN-I1.7	1132	85	74	22	100%	08h19
	HN-I2.0	991	93	71	22	100%	09h46
	HN-I2.5	1185	112	74	24	96%	10h00
	HN-I3.0	1110	107	73	32	91%	10h00

Table 1. Experimental Results on HN-I Instances.

Figure 6 compares the convergence of the CPG and CPG-CF approaches measured as the percentage of evacuees in the incumbent solution over time for the 8 instances and 10 runs. Interestingly, it appears that for instances HN to HN-I1.4 (CPG) and HN-I-2.0 (CPG-CF), the first solution already evacuates as many evacuees as in the final solution. As expected, CPG-CF shows a steeper convergence. It is worth noting that a similar analysis for the evacuation duration shows that CPG stagnates at the initial value, while CPG-CF finds gradually improving solutions.

Table 2 presents the same statistics for the New Orleans case study. Values reported are either the average over the 10 runs (avg.) or the value of the solution with the lowest evacuation time (best). The results confirms the observations made for HN: in the New Orleans case, the evacuation takes on average 37% less time when allowing contraflows. CPG-CF is able to evacuate the whole Greater New Orleans region in less than 40 hours. On the other hand, CPG can only complete the evacuation in about 60 hours, much more than the 48 hours available for the Katrina evacuation. As a result, about 80,000 vehicles would be left behind.

Solver		Num. Paths	Num. Cols (10^3)	Num. Rows (10^3)	CPU Time (min)	Perc. Evac.	Evac. Time
CPG	**avg.**	3741	567	712	131	100%	60h48
	best	3398	506	712	92	100%	59h40
CPG-CF72	**avg.**	3818	355	872	152	100%	39h53
	best	3938	361	880	153	100%	37h00

Table 2. Experimental Results on the New Orleans Instance.

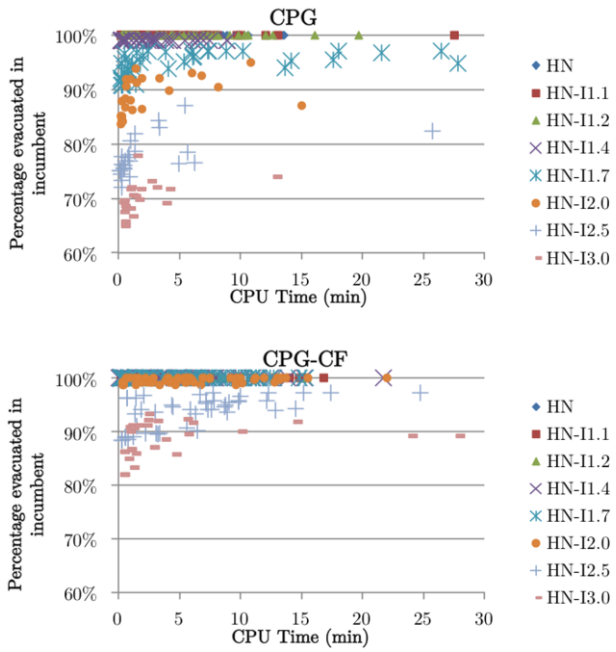

Figure 6. Solution quality vs. CPU Time for CPG and CPG-CF.

7 Conclusion

This paper proposed a conflict-based path-generation heuristic for evacuation planning with contraflows (CPG-CF). The approach borrows concepts from column generation and decomposes the evacuation planning problem with contraflows (EPP-CF) in a master problem and a path generation subproblem. While the subproblem generates diverse evacuation paths, the master problem assigns paths to evacuated areas and schedules the evacuation. To the best of our knowledge, CPG-CF is the first approach to consider the design of evacuation plans and the selection of contraflow roads jointly. The CPG output is a high-quality evacuation plan operating at a fine granularity: It includes a route and an evacuation schedule for each evacuated area at each time step. The CPG-CF model further enhances this plan with contraflow decisions for a selected set of roads.

The CPG and CPG-CF models were applied to the planning of large-scale evacuations involving from 70,000 to 1,000,000 people. The experimental results demonstrated the significant benefits of contraflows which improve the evacuation time by up to 37% in both the New Orleans and Hawkesbury Nepean evacuations. The evacuation plans were computed in reasonable time when compared to the evacuation horizon.

Finally, the paper presented a web-based intelligent system that allows local authorities and emergency services to model, plan, and simulate evacuations, enabling rapid evacuation planning and what-if scenario analysis.

Future work will focus on refining the modeling of the flow of evacuees entering and leaving contraflow roads. In particular, we are interested in assigning evacuation areas to different lanes depending on the side of the road from which they enter the contraflow. In addition, practical evidence suggests that diverging flows can lead to confusion among evacuees and create additional congestion. We are currently developing models that attempt to address these two issues, while retaining the benefits of contraflow.

ACKNOWLEDGEMENTS

NICTA is funded by the Australian Government through the Department of Communications and the Australian Research Council through the ICT Centre of Excellence Program.

REFERENCES

[1] Douglas R. Bish and Hanif D. Sherali, 'Aggregate-level demand management in evacuation planning', *European Journal of Operational Research*, **224**(1), 79–92, (2013).

[2] S. Bretschneider and A. Kimms, 'Pattern-based evacuation planning for urban areas', *European Journal of Operational Research*, **216**(1), 57–69, (2012).

[3] Carlos F. Daganzo, 'The cell transmission model: A dynamic representation of highway traffic consistent with the hydrodynamic theory', *Transportation Research Part B: Methodological*, **28**(4), 269–287, (1994).

[4] Horst W. Hamacher and Stevanus A. Tjandra, 'Mathematical modelling of evacuation problems: A state of art', Technical report, Fraunhofer Institut für Techno und Wirtschaftsmathematik, (2001).

[5] Olga Huibregtse, Andreas Hegyi, and Serge Hoogendoorn, 'Blocking roads to increase the evacuation efficiency', *Journal of Advanced Transportation*, **46**(3), 282–289, (2012).

[6] Olga L. Huibregtse, Michiel C.J. Bliemer, and Serge P. Hoogendoorn, 'Analysis of near-optimal evacuation instructions', *Procedia Engineering*, **3**(0), 189–203, (2010). 1st Conference on Evacuation Modeling and Management.

[7] Olga L. Huibregtse, Serge P. Hoogendoorn, Andreas Hegyi, and Michiel C. J. Bliemer, 'A method to optimize evacuation instructions', *OR Spectrum*, **33**(3), 595–627, (2011).

[8] Sangho Kim, Shashi Shekhar, and M. Min, 'Contraflow transportation network reconfiguration for evacuation route planning', *Knowledge and Data Engineering, IEEE Transactions on*, **20**(8), 1115–1129, (2008).

[9] Gino J. Lim, Shabnam Zangeneh, M. Reza Baharnemati, and Tiravat Assavapokee, 'A capacitated network flow optimization approach for short notice evacuation planning', *European Journal of Operational Research*, **223**(1), 234–245, (2012).

[10] Henry X Liu, Xiaozheng He, and Xuegang Ban, 'A cell-based many-to-one dynamic system optimal model and its heuristic solution method for emergency evacuation', in *Proc. 86th Annual Meeting Transportation Res. Board*, (2007).

[11] Qingsong Lu, Betsy George, and Shashi Shekhar, 'Capacity constrained routing algorithms for evacuation planning: A summary of results', in *Advances in Spatial and Temporal Databases*, volume 3633 of *Lecture Notes in Computer Science*, 291–307, Springer Berlin Heidelberg, (2005).

[12] Deborah Matherly, *A Transportation Guide for All-Hazards Emergency Evacuation*, Transportation Research Board, 2012.

[13] Pamela Murray-Tuite and Brian Wolshon, 'Evacuation transportation modeling: An overview of research, development, and practice', *Transportation Research Part C: Emerging Technologies*, **27**, 25–45, (2013).

[14] Victor Pillac, Pascal Van Hentenryck, and Caroline Even, 'A conflict-based path-generation heuristic for evacuation planning', Technical Report VRL-7393, NICTA, (2013). arXiv:1309.2693, submitted for publication.

[15] Kai-Florian Richter, Mingzheng Shi, Heng-Soon Gan, and Stephan Winter, 'Decentralized evacuation management', *Transportation Research Part C: Emerging Technologies*, **31**(0), 1–17, (2013).

[16] Paul Brian Wolshon, *Transportation's Role in Emergency Evacuation and Reentry*, Transportation Research Board, 2009.

[17] Chi Xie and Mark A. Turnquist, 'Lane-based evacuation network optimization: An integrated lagrangian relaxation and tabu search approach', *Transportation Research Part C: Emerging Technologies*, **19**(1), 40–63, (2011).