Large-Scale Evacuation Planning

Actionable Evacuation Plans With Contraflows

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About NICTA - ORG

• NICTA
  • 5 research groups
  • 3 business teams
  • 15 startups

• Optimisation Research Group (ORG)
  • ~60 staff & PhDs
Credits

Victor Pillac
Pascal Van Hentenryck
Caron Chen
Disaster management

• **Pre-Katrina:**
  Focus on providing situational awareness
  *What is happening?*

• **Post-Katrina:**
  Need for advanced decision support
  *How can we mitigate negative effects and use resources more effectively?*

“The Federal government must develop the capacity to conduct large-scale logistical operations.”
(p 56)
Motivation
Motivation

Warragamba dam
Motivation

Warragamba dam

1-in-1000 flood event:
Cost: $8 billion
80,000 people to evacuate
Evacuation planning

• Decisions
  • When to evacuate
  • Where to go?
  • Which route to follow?

• Constraints
  • Avoid congestion
  • Ensure safety of evacuees
Evacuation planning

- **Decisions**
  - When to evacuate
  - Where to go?
  - Which route to follow?

- **Constraints**
  - Avoid congestion
  - Ensure safety of evacuees
Evacuation of 80,000 persons
Evacuation of 80,000 persons
Evacuation Scenario

Real-world scenario

Evacuation graph
Evacuation Scenario

Real-world scenario

Evacuation graph
Evacuation Scenario

Real-world scenario

Evacuated area

Safe zone

Evacuation graph

(1,10,11:00)

(1,10,11:00)

(1,10,11:00)

(1,10,11:00)

(1,10,∞)

(1,10,9:00)

(1,10,9:00)

(2,5,13:00)

(20,13:00)
Evacuation Scenario

Real-world scenario

Evacuation graph
Evacuation Scenario

Real-world scenario

Evacuation graph

(1,10,11:00)

(1,10,9:00)

(1,10,11:00)

(1,10,11:00)

(2,5,13:00)

(20,13:00)

(1,10,∞)

Safe zone

Roads and intersections

Evacuated area

(travel time, capacity, closed time)
Evacuation Scenario

Real-world scenario

Evacuation graph

Safe zone

Roads and intersections

Evacuated area

(travel time, capacity, closed time)

(demand, evac. deadline)
Evacuation Scenario

Real-world scenario

Evacuation graph

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Contraflows

- Increase outbound capacity by changing lane direction
- In practice: highways and major roads

Houston, TX
Contraflows

- Increase outbound capacity by changing lane direction
- In practice: highways and major roads

Houston, TX
Contraflows

• Increase outbound capacity by changing lane direction

• In practice: highways and major roads

Houston, TX
Evacuation Scheduling

• The problem is to schedule the evacuation over time
  • Given evacuation routes
  • Decide when each evacuee leaves

• Modeled using a Time-Expanded Graph:

Node 0 at time 9:00

Travel from node 2 to node B leaving at 10:00 arriving at 11:00
Evacuation Scheduling

Evacuation route

Evacuation schedule
Evacuation Scheduling

Evacuation route

Evacuation schedule
Evacuation Scheduling

5 leaving at 9:00

Evacuation route

Evacuation schedule
Evacuation Scheduling

5 leaving at 9:00

5 leaving at 10:00

Evacuation route

Evacuation schedule
Evacuation Scheduling

Evacuation route

Evacuation schedule
State Of The Art

- Most approaches rely on free flow models
  - Solve a max flow problem on the time-expanded graph

- Limitations
  - No detailed instructions to evacuees (no evacuation route)
  - Underestimate the time required for evacuation
Conflict Path Generation (CPG)

- Start
- Generate initial paths
- Solve the master problem
- Identify critical nodes C
  - C=∅?
    - NO: Generate new paths for nodes in C
    - YES: Add conflicting nodes to C
- End
Conflict Path Generation (CPG)

Start

Generate initial paths

Solve the master problem

Identify critical nodes $C$

$C=\emptyset$?

End

Add conflicting nodes to $C$
Approach Overview

Start

Generate initial paths

Solve the master problem

Identify critical nodes C

C=∅?

YES

End

NO

Generate new paths for nodes in C

Add conflicting nodes to C
Reduced Master Problem 1

\[
\begin{align*}
\text{max} & \quad \sum_{p \in \Omega} \sum_{t \in \mathcal{H}_p} \varphi_t^p \\
\text{s.t.} & \quad \sum_{p \in \Omega_k} x_p = 1 \quad \forall k \in \mathcal{E} \\
& \quad \sum_{p \in \Omega_k} \sum_{t \in \mathcal{H}_p} \varphi_t^p + \varphi_k = d_k \quad \forall k \in \mathcal{E} \\
& \quad \sum_{p \in \omega(e)} \varphi_t^{t-\tau_e^p} \leq u_e \quad \forall e \in \mathcal{A} \setminus \mathcal{A}_c, t \in \mathcal{H} \\
& \quad \sum_{p \in \omega(e)} \varphi_t^{t-\tau_e^p} \leq y_e u_e + (1-y_e)u_e \quad e \in \mathcal{A}_c, t \in \mathcal{H} \\
& \quad y_e + y_{\bar{e}} \geq 1 \quad \forall e \in \mathcal{A}_c \\
& \quad y_e \geq x_p \quad \forall e \in \mathcal{A}_c, \forall p \in \omega(e) \\
& \quad \sum_{t \in \mathcal{H}_p} \varphi_t^p \leq |\mathcal{H}_p| x_p u_p \quad \forall p \in \Omega \\
& \quad \varphi_t^p \geq 0 \quad \forall p \in \Omega, t \in \mathcal{H}_p \\
& \quad \varphi_k \geq 0 \quad \forall k \in \mathcal{E} \\
& \quad y_e \in \{0,1\} \quad \forall e \in \mathcal{A}_c \\
& \quad x_p \in \{0,1\} \quad \forall p \in \Omega
\end{align*}
\]
Reduced Master Problem 1

\[
\text{max} \quad \sum_{p \in \Omega} \sum_{t \in \mathcal{H}_p} \varphi^p_t \\
\text{s.t.} \quad \sum_{p \in \Omega_k} x_p = 1 \quad \forall k \in \mathcal{E} \\
\sum_{p \in \Omega_k} \sum_{t \in \mathcal{H}_p} \varphi^t + \varphi_k = d_k \quad \forall k \in \mathcal{E} \\
\sum_{p \in \omega(e)} \sum_{t - \tau^e_p \in \mathcal{H}_p} \varphi^{t - \tau^e_p} \leq u_e \quad \forall e \in \mathcal{A} \setminus \mathcal{A}_c, t \in \mathcal{H} \\
\sum_{p \in \omega(e)} \sum_{t - \tau^e_p \in \mathcal{H}_p} \varphi^{t - \tau^e_p} \leq y_e u_e + (1 - y_e) u_e \quad e \in \mathcal{A}_c, t \in \mathcal{H} \\
y_e + y_e \geq 1 \quad \forall e \in \tilde{\mathcal{A}}_c \\
y_e \geq x_p \quad \forall e \in \mathcal{A}_c, \forall p \in \omega(e) \\
\sum_{t \in \mathcal{H}_p} \varphi^t \leq |\mathcal{H}_p| x_p u_p \quad \forall p \in \Omega \\
\varphi^t \geq 0 \quad \forall p \in \Omega, t \in \mathcal{H}_p \\
\varphi_k \geq 0 \quad \forall k \in \mathcal{E} \\
y_e \in \{0, 1\} \quad \forall e \in \mathcal{A}_c \\
x_p \in \{0, 1\} \quad \forall p \in \Omega
\]
Reduced Master Problem 1

\[
\begin{align*}
\text{max} & \quad \sum_{p \in \Omega} \sum_{t \in \mathcal{H}_p} \varphi^p_t \\
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& \quad \sum_{p \in \Omega} \sum_{t \in \mathcal{H}_p} \varphi^t_p + \varphi_k = d_k \\
& \quad \sum_{p \in \omega(e)} \sum_{t \in \mathcal{H}_p \setminus \mathcal{E}_p} \varphi^t_p \leq u_e \\
& \quad \sum_{p \in \omega(e)} \sum_{t \in \mathcal{H}_p \setminus \mathcal{E}_p} \varphi^t_p \leq y_e u_e + (1 - y_e) u_e \\
& \quad y_e + y_e \geq 1 \\
& \quad y_e \geq x_p \\
& \quad \sum_{t \in \mathcal{H}_p} \varphi^t_p \leq \mathcal{H}_p x_p u_p \\
& \quad \varphi^t_p \geq 0 \\
& \quad \varphi_k \geq 0 \\
& \quad y_e \in \{0, 1\} \\
& \quad x_p \in \{0, 1\}
\end{align*}
\]

Max. number of evacuees reaching safety

Select one path per evacuated area
Reduced Master Problem 1

\[
\begin{align*}
\text{max} & \quad \sum_{p \in \Omega} \sum_{t \in \mathcal{H}_p} \varphi^p_t \\
\text{s.t.} & \quad \sum_{p \in \Omega} x_p = 1 \\
& \quad \sum_{p \in \Omega} \sum_{t \in \mathcal{H}_p} \varphi^t_p + \varphi_k = d_k \\
& \quad \sum_{p \in \omega(e)} \sum_{t-\tau^e_p \in \mathcal{H}_p} \varphi^t_{p-\tau^e_p} \leq u_e \\
& \quad \sum_{\omega(e)} \sum_{t-\tau^e_p \in \mathcal{H}_p} \varphi^t_{p-\tau^e_p} \leq y_e u_e + (1 - y_e) u_e \\
& \quad y_e + y_e \geq 1 \\
& \quad y_e \geq x_p \\
& \quad \sum_{t \in \mathcal{H}_p} \varphi^t_p \leq |\mathcal{H}_p| x_p u_p \\
& \quad \varphi^t_p \geq 0 \\
& \quad \varphi_k \geq 0 \\
& \quad y_e \in \{0, 1\} \\
& \quad x_p \in \{0, 1\}
\end{align*}
\]

Max. number of evacuees reaching safety

Select one path per evacuated area

Account for non evacuated vehicles

\[
\forall e \in \mathcal{A} \setminus \mathcal{A}_c, t \in \mathcal{H}
\]
Reduced Master Problem 1

\[
\text{max} \quad \sum_{p \in \Omega} \sum_{t \in \mathcal{H}_p} \varphi_t^p \\
\text{s.t.} \quad \sum_{p \in \Omega_k} x_p = 1 \\
\sum_{p \in \Omega_k} \sum_{t \in \mathcal{H}_p} \varphi_t^p + \varphi_k = d_k \\
\sum_{p \in \omega(e)} \varphi_{t-\tau_p}^{t-\tau_p} \leq u_e \\
\sum_{p \in \omega(e)} \varphi_{t-\tau_p}^{t-\tau_p} \leq y_e u_e + (1 - y_e) u_e \\
y_e + y_e \geq 1 \\
y_e \geq x_p \\
\sum_{t \in \mathcal{H}_p} \varphi_t^p \leq |\mathcal{H}_p| x_p u_p \\
\varphi_t^p \geq 0 \\
\varphi_k \geq 0 \\
y_e \in \{0, 1\} \\
x_p \in \{0, 1\}
\]

Max. number of evacuees reaching safety

Select one path per evacuated area

Account for non evacuated vehicles

Edge capacity & Contraflow decisions
Reduced Master Problem 1

\[
\begin{align*}
\text{max} & \quad \sum_{p \in \Omega} \sum_{t \in \mathcal{H}_p} \varphi_t^p \\
\text{s.t.} & \quad \sum_{p \in \Omega_k} x_p = 1 \\
& \quad \sum_{p \in \Omega_k} \sum_{t \in \mathcal{H}_p} \varphi_t^p + \varphi_k = d_k \\
& \quad \sum_{p \in \omega(e)} \sum_{t-\tau_p^e \in \mathcal{H}_p} \varphi_{t-\tau_p^e}^p \leq u_e \\
& \quad \sum_{p \in \omega(e)} \sum_{t-\tau_p^e \in \mathcal{H}_p} \varphi_{t-\tau_p^e}^p \leq y_e u_e + (1 - y_e) u_e \\
& \quad y_e + y_e \geq 1 \\
& \quad y_e \geq x_p \\
& \quad \sum_{t \in \mathcal{H}_p} \varphi_t^p \leq |\mathcal{H}_p| x_p u_p \\
& \quad \varphi_t^p \geq 0 \\
& \quad \varphi_k \geq 0 \\
& \quad y_e \in \{0, 1\} \\
& \quad x_p \in \{0, 1\}
\end{align*}
\]

- Max. number of evacuees reaching safety
- Select one path per evacuated area
- Account for non evacuated vehicles
- Edge capacity & Contraflow decisions
- Link flow and path selection variables
Reduced Master Problem 1

\[ \begin{align*}
\text{max} & \quad \sum_{p \in \Omega} \sum_{t \in \mathcal{H}_p} \varphi^p_t \\
\text{s.t.} & \quad \sum_{p \in \Omega} x_p = 1 \\
& \quad \sum_{p \in \Omega} \sum_{t \in \mathcal{H}_p} (\varphi^t_p + \varphi^t_k) \leq \vartheta \\
& \quad \sum_{p \in \omega(e)} \varphi^{t-\tau_p^e}_p \leq \gamma_{e} \\
& \quad \sum_{p \in \omega(e)} \varphi^{t-\tau_p^e}_p \leq \gamma_{e} \\
& \quad y_e + y_e^c \geq 1 \\
& \quad y_e \geq x_p \\
& \quad \sum_{t \in \mathcal{H}_p} \varphi^t_p \leq |\mathcal{H}_p| x_p u_p \\
& \quad \varphi^t_p \geq 0 \\
& \quad \varphi^t_k \geq 0 \\
& \quad y_e \in \{0, 1\} \\
& \quad x_p \in \{0, 1\}
\end{align*} \]

**Advantages:**
- Adds variables and constraints only when needed
- Factor 100 reduction in number of variables and constraints

\[ \forall e \in \mathcal{A}_c, \forall p \in \omega(e) \]

\[ \forall p \in \Omega, t \in \mathcal{H}_p \]
\[ \forall k \in \mathcal{E} \]
\[ \forall e \in \mathcal{A}_c \]
\[ \forall p \in \Omega \]
Reduced Master Problem 2

• Structure of the master problem:
Reduced Master Problem 2

- Structure of the master problem:

\[
\{ \varphi^p_t, x_p \mid p \in \Omega, t \in \mathcal{H} \}
\]

Each new path adds new constraints
Approach Overview

Start

Generate initial paths

Solve the master problem

Identify critical nodes C

C=∅?

YES

End

NO

Generate new paths for nodes in C

Add conflicting nodes to C
Critical Evacuated Nodes

A

B

C

D

E

10/10

5/10

5/5

10/10

20

20

10

10

5

5

5
Critical Evacuated Nodes

Critical node

10/10
A

5/10
B

5/5
C

20
20

Critical node

5/10

10

10

5

5
Critical Evacuated Nodes

Critical node

Saturated edge shared by B and C
Critical Evacuated Nodes

- Critical node: A
- Conflicting node: B, C
- Saturated edge shared by B and C

The diagram illustrates the flow and evacuation routes, with critical and conflicting nodes marked accordingly.
Critical Evacuated Nodes

Goal: generate paths that avoid this edge

Critical node
Conflicting node
Saturated edge shared by B and C
Critical Evacuated Nodes

Goal: generate paths that avoid this edge

Critical node

Conflicting node

Saturated edge shared by B and C
Critical Evacuated Nodes
Critical Evacuated Nodes
Approach Overview

1. Start
2. Generate initial paths
3. Solve the master scheduling problem
4. Identify critical nodes \( C \)
   - If \( C = \emptyset \), then:
     - Add conflicting nodes to \( C \)
     - Generate new paths for nodes in \( C \)
   - If \( C \neq \emptyset \), then:
     - End
Heuristic Path Generation (HPG)

- Generate paths without considering the evacuation schedule
- Shortest path in the evacuation graph
- Penalize edges depending on current solution

Edge travel time + Number of time the edge was used + Average utilization in current solution + Random noise
Conflict Path Generation (CPG)

1. Start
2. Generate initial paths
3. Solve the master problem
4. Identify critical nodes \( C \)
5. \( C = \emptyset \)?
   - NO: Add conflicting nodes to \( C \), generate new paths for nodes in \( C \)
   - YES: End

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## Computational experiments

<table>
<thead>
<tr>
<th>Instance</th>
<th>Contraflow</th>
<th>Num. evac.</th>
<th>Num. nodes</th>
<th>Num. paths</th>
<th>CPU (min)</th>
<th>Perc. Evac.</th>
<th>Evac. Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hawkesbury Nepean</td>
<td>No</td>
<td>70k</td>
<td>170</td>
<td>1014</td>
<td>15</td>
<td>100%</td>
<td>8h05</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>70k</td>
<td>170</td>
<td>1125</td>
<td>6</td>
<td>100%</td>
<td>5h34</td>
</tr>
<tr>
<td>New Orleans</td>
<td>No</td>
<td>1m</td>
<td>2000</td>
<td>3741</td>
<td>131</td>
<td>100%</td>
<td>60h48</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>1m</td>
<td>2000</td>
<td>3818</td>
<td>152</td>
<td>100%</td>
<td>39h53</td>
</tr>
</tbody>
</table>
NICTA Evacuation Planner

1. Road network
   Population data
   Threat scenarios

2. Evacuation network
   Evacuated areas
   Safe nodes

3. Web interface

4. Optimization module
   Evacuation plan
NICTA Evacuation Planner

Select Project
- Canberra
- New Orleans
- Hawkesbury Nepean

Confirm
NICTA Evacuation Planner
Take away

• Evacuations are a critical aspect of disaster management
  • Evacuation planners heavily rely on expert knowledge
  • Decision support systems are needed!

• Conflict based path generation
  • General decomposition approach
  • Leverage domain knowledge to generate new columns
  • Useful when the Master Problem is a MIP
Perspectives

• Current work
  • Include evacuees behavior in optimization
  • Traditional column generation approach
  • Refine modeling of the road network
  • Deploy with an emergency service partner

• Extensions
  • Model operational cost of contraflow
  • Agent based simulation including behaviors