A Stochastic Integer Programming Extended Attack Response Model for Large-Scale Wildfires

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Agenda

Problem Setting

Literature Review

Methodology
  Simulation-Optimization Approach
  SMIP Optimization Model

Example Illustration

Summary
Wildfire Statistics

There is an increasing trend in the number and size of large-scale wildfires

- 76,000 wildfires in the U.S. each year from 2001 to 2011, which burned 7 million acres (2.8 million ha) (National Interagency Fire Center)

- 2011 Texas Wildfire Season (November 15, 2010-October 31, 2011):
  - 31,453 fires
  - 4.011 million acres burned (1.65 million ha)
  - 2,947 homes lost (39,413 saved)
  - 12 fatalities

- Bastrop, TX, USA
  - Sept. 4, 2011 - Sept. 30, 2011
  - Cause: electrical fire
  - 1669 homes lost
  - 34,068 acres burned (13,790 ha)
Introduction

- *Initial attack* are the actions taken by the first resources to arrive at a wildfire to protect lives and property, and prevent further extension of the fire.

- *Extended wildfire response planning* follows if the fires escape initial attack.

- *Large-scale wildfires* are those that have escaped initial attack due to extreme burning conditions.

**Figure:** A wildfire in Yarnell, Arizona, USA killed 19 firefighters on Sunday, June 30, 2013.
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Introduction
Problem Setting

Introduction

- We consider *indirect attack*, a method of *fire suppression* that works to contain wildfires by establishing control lines away from a fire that contain no combustible materials

- *Firefighting resources* (e.g., bulldozers, air tankers, plows, personnel, etc.) are used to establish control lines around a wildfire

- A *dispatch decision* is the assignment of a firefighting resource to a location at a specific time.

Figure: Bulldozer
Introduction

- Weather conditions can heavily impact fire spread.

Where should you dispatch resources?

Wind Speed: 19.6 m/s
Direction: 67° (azimuth)

Wind Speed: 19.5 m/s
Direction: 48°

Wind Speed: 5.4 m/s
Direction: 348°

Scenario 1
Vegetation
Burned
Burning

Scenario 2

Scenario 3
Initial fire footprint
Wildfire Resource Scheduling Challenges

Research Goal:
Determine optimal location and timing of firefighting resources to an escaped large-scale wildfire under uncertain weather conditions
Wildfire Resource Scheduling Challenges

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Determine optimal location and timing of firefighting resources to an escaped large-scale wildfire under uncertain weather conditions

Challenges:

► Wildfire resource safety concerns

► Resource travel time

► Predicting fire growth

► Uncertain weather conditions influence fire growth predictions

► Dispatch decisions also impact fire behavior predictions
## Literature Review

<table>
<thead>
<tr>
<th>Fire Modeling</th>
<th>Reference</th>
<th>Description</th>
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<tbody>
<tr>
<td></td>
<td>(Finney, 1998)</td>
<td>FARSITE: Fire area simulator.</td>
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<tr>
<td></td>
<td>(Andrews et al., 2005)</td>
<td>BehavePlus fire modeling system.</td>
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<tr>
<td></td>
<td>(Finney, 2006)</td>
<td>FlamMap fire modeling capabilities.</td>
</tr>
<tr>
<td></td>
<td>(Ntaimo et al., 2008)</td>
<td>DEVS-FIRE Integrated simulation of wildfire spread and containment. Designed to be integrated with stochastic optimization models.</td>
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<th>Fire Management and Initial Attack</th>
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<th>Description</th>
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<tr>
<td></td>
<td>(Hof et al., 2000)</td>
<td>Investigate fire management through spatial optimization to reduce fuel loads and protect valuable assets.</td>
</tr>
<tr>
<td></td>
<td>(Wei et al., 2008)</td>
<td>MIP model to locate fuel treatment over spatial landscape to minimize expected fire losses under budget constraints and domino effects for suppression.</td>
</tr>
<tr>
<td></td>
<td>(Hu and Ntaimo, 2009)</td>
<td>Used a two-stage SMIP for initial deployment to test firefighting tactics.</td>
</tr>
<tr>
<td></td>
<td>(Ntaimo et al., 2012)</td>
<td>SMIP for wildfire initial attack planning; goal is to contain as many fires as possible while minimizing fixed rental and travel costs and expected future operational costs.</td>
</tr>
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<th>Large Scale Wildfires and Spatial Opt.</th>
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<th>Description</th>
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<tbody>
<tr>
<td></td>
<td>(Mees and Strauss, 1992)</td>
<td>Allocating resources to large wildfires with stochastic production rates.</td>
</tr>
<tr>
<td></td>
<td>(Finney et al., 2009)</td>
<td>Model probability of containment of large wildfires and determine what factors influence successful containment.</td>
</tr>
<tr>
<td></td>
<td>(Thompson et al., 2011)</td>
<td>Large-scale wildfire risk assessment.</td>
</tr>
<tr>
<td></td>
<td>(Calkin et al., 2011)</td>
<td>Real-time risk assessment tool for decision-making of large-scale wildfires.</td>
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</table>
Simulation-Optimization Approach

Fire behavior simulation (eg. DEVS-FIRE, FlamMap)
- Generates fire growth scenarios based on stochastic weather data

Stochastic optimization
- Uses fire growth scenarios to make dispatch decisions using a stochastic mixed-integer program (SMIP)

Fire behavior and fire suppression simulation
- Assesses dispatch decisions for the real weather conditions

Figure: Optimization and simulation relationship
Methodology

Simulation-Optimization Approach

Figure: Optimization and simulation relationship
Texas Wildfire Risk Assessment (TWRA) System

- **Fire Response Accessibility Index (FRAI):** A relative measure of how long it would take initial attack resources to drive from their resource location to each fire area, index range 1 (easily accessible) to 6 (inaccessible).

- **Dozer Operability Rating (DOR):** A measure of the difficulty to operate equipment and resources for suppressing fires, index range 1 (easily operable) to 9 (inoperable).
Scenarios

- Fire behavior simulation model (eg. DEVS-FIRE, FlamMap) simulates fire behavior each possible weather condition
- A *scenario* is a realization of fire behavior defined by:
  - fire arrival time to a cell
  - fire rate of spread
  - spread direction
  - fireline intensity

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A Stochastic Programming Extended Attack Response Model for Large-Scale Wildfires
Multi-period Two-stage SMIP Optimization Model

- Two-stage SMIP
  - binary first-stage decisions
  - fixed recourse, random technology matrix
  - continuous second-stage decisions

- Decisions
  - First-stage:
    - Which cells to target for suppression
    - Sequence each resource suppresses the targeted cells
  - Second-stage:
    - Unfinished line construction (distance) in each cell

- Objective
  - First-stage:
    - Identify cells that are easily accessible (low FRAI)
    - Identify cells that are easily operable (low DOR)
  - Second-stage:
    - Minimize unfinished line construction in each cell
SMIP Model First-stage Decision Variables

For each decision period \( t = 0, 2, \ldots, T - 1 \)

\[
\begin{align*}
    x^t_j : & \quad x^t_j = 1 \text{ if target cell } j \text{ is scheduled for suppression in period } t, \ x^t_j = 0 \text{ otherwise} \\
    z^{t}_{r(k)ij} : & \quad y^{t}_{r(k)ij} = 1 \text{ if resource } r(k) \text{ is assigned to suppress cell } j \\
                     & \quad \text{in sequence slot } i \text{ during period } t, \ z^{t}_{r(k)ij} = 0 \text{ otherwise}
\end{align*}
\]

Figure: Variable \( y \) selects a sequence \((i = 0, \ldots, \bar{I})\) of cells \( j \) for each resource \( r \).
SMIP Model: First-stage

For each decision period \( t = 0, 2, ..., T - 1 \)

Minimize

\[
\sum_{r(k) \in R(k) \setminus \bar{I}_t} \sum_{i \in \{1, ..., n_{r(k)} \}} \sum_{j \in J_{r(k)}} w_{ij}^t (DOR_j + FRAI_{r,k}) z_{r(k)}^{t,ij} + E[f(x, z, \bar{\omega})]
\]

\[
\sum_{j \in J_t} x_j^t \leq u^t
\]

\[
\sum_{r(k) \in R(j) \setminus \bar{J}_t} \sum_{i \in I_t} z_{r(k)}^{t,ij} \leq m_j x_j^t, \quad \forall j \in J^t
\]

\[
z_{r(k)}^{t,ij} - x_j^t \leq 0, \quad \forall r(k) \in R(k)^t, \forall i \in I^t, \forall j \in J^t
\]

\[
x_j^t - \sum_{r(k) \in R(j) \setminus \bar{J}_t} \sum_{i \in I_t} z_{r(k)}^{t,ij} \leq 0, \quad \forall j \in J^t
\]

\[
\sum_{i \in I_t} z_{r(k)}^{t,ij} \leq 1, \quad \forall r(k) \in R(k)^t, \forall j \in J_{r(k)}^t
\]

\[
z_{r(k)}^{t,0j} = 1
\]

\[
\sum_{j \in N_{j} \setminus J_{r(k)}^t} z_{r(k)}^{t,(i+1)j} - z_{r(k)}^{t,ij} \geq 0
\]

\[
x_j^t \in \{0, 1\}, \quad \forall j \in J^t
\]

\[
z_{r(k)}^{t,ij} \in \{0, 1\}, \quad \forall r(k) \in R(k)^t, \forall i \in I^t \setminus \bar{I}_t, \forall j \in J_{r(k)}^t
\]
SMIP Model: First-stage Constraints for Decision Period $t$

(1) Upperbound $u^t$ on the number of cells can be selected for suppression in decision period $t$

(2) Upperbound $m_j$ resources can be assigned to cell $j$ in decision period $t$

(3) A resource cannot be assigned to a cell unless the cell has been selected for suppression

(4) Each cell selected for suppression must have at least one resource deployed (assigned) to it

(5) Each cell $j$ can only be assigned to resource $r(k)$ once in the sequence

(6) Initialize the resource’s initial location in the sequence

(7) The next cell in the sequence for resource $r(k)$ should be a neighbor cell and be in set $J^t_{r(k)}$

(8-9) Binary restrictions
SMIP Model: Second-stage Decision Variables

For each decision period $t = 0, 2, ..., T - 1$

$y^t_j(\omega)$: amount of line construction remaining in cell $j$ at the end of period $t$ in scenario $\omega$
SMIP Model: Second-stage Objective for Decision Period $t$

$$f(x, z, \omega) = \text{Minimize} \sum_{j \in J^t} p_j \cdot y_j^t(\omega)$$

$$-y_j^t(\omega) \leq \sum_{r(k) \in \{r(k) | r(k) \in R(k)^t, j \in J^t_{r(k)}\}} \sum_{i \in I^t} \alpha_{r(k)j}^t \pi_{r(k)j}^t(\omega) z_{r(k)ij}^t - l_j^t \quad \forall j \in J^t \quad (1)$$

$$y_j^t(\omega) \geq 0 \quad \forall j \in J^t \quad (2)$$

The sum of the line construction efforts of resources $r(k)$ deployed to cell $j$ must meet or exceed the line construction required for cell $j$ selected for suppression

Non-negativity constraints
Illustration

- 4000 cell example (30m x 30m)
- 2 weather scenarios
- 10 resources
  - line construction is 0.35 km/hr
- 1 cell initially on fire
- Decisions made every hour

Example SMIP solved using CPLEX
Illustration

Figure: Fire spread after 6 hours without suppression
Illustration: $t=0$

Figure: Initial fire and resource locations
Illustration: $t = 0$

Figure: $t=0$: Scenario 1 predictions for the next hour

Figure: $t=0$: Scenario 2 predictions for the next hour
Illustration: $t=1$

Figure: Suppression and Fire Spread at $t=1$ (1 hour) if scenario 2 was realized
Illustration: $t = 0$

**Figure:** $t=0$: Scenario 1 predictions for the next hour

**Figure:** $t=0$: Scenario 2 predictions for the next hour
Next Steps

- Improve model to complete containment line
- Validate with the Rockhouse fire data
  - April 9-May 6, 2011
  - 314,444 acres burned (127,000 ha)
- Analysis on decision frequency
- Protection vs. suppression of valuable resources
Wildfires take lives, burn structures, and destroy natural habitats

Developed a simulation and optimization approach to large-scale wildfire extended-attack planning

Formulation of a SMIP for wildfire extended attack planning

Next steps are to improve the SMIP model and evaluate using real Texas wildfire data
Questions?

Thank You!
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Selected References

- Science Daily [www.sciencedaily.com](http://www.sciencedaily.com)
- Texas Forest Service [txforestservice.tamu.edu/](http://txforestservice.tamu.edu/)
- Wildfire Today [www.wildfiredtoday.com](http://www.wildfiredtoday.com)