Minimum Cost Flow Interdiction with Shifting and Recruiting for Human Trafficking Networks

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What is our model?

A bilevel mixed integer linear program

$$\max_{y} \min_{x,\bar{\beta},q,p} \sum_{t=1}^{T} \sum_{(i,j)\in A} c_{ij} x_{ij}^t$$

maximize the minimum cost flow over time

Subject to the following constraints:

Revenue Flow and Demand

$$\sum_{j\in\delta^+(i)} x_{ji}^t + u_i^t = \sum_{j\in\delta^-(i)} x_{ij}^t \qquad \forall i \in N,\, t \in T$$

flow in + production = flow out

$$b_a + \bar{\beta}_a^t = \sum_{\delta^+(a)} x_{ia}^t, \qquad \forall t \in T$$

trafficker demand = flow in

$$0 \le x_{ii'}^t \le M\left(1 - \sum_{\tau=1}^{t} y_{ii'}^{\tau}\right) \qquad \forall (i,i') \in A^E,\, t \in T$$

interdicting arcs closes flow

$$u_i^t \le (b_i + \bar{\beta}_i^t)\left(1 - \sum_{\tau=1}^{\tau} y_{i'i''}^{\tau}\right) \qquad \forall i \in N,\, t \in T$$

production bounded by available supply

$$b_i + \bar{\beta}_i^t \le B_i \qquad \forall i \in N,\, t \in T$$

maximum supply for node

$$\bar{\beta}_a^t \ge \left(\sum_{i\in V\cup B} (b_i + \bar{\beta}_i^t)\left(1 - \sum_{\tau=1}^{t} y_{ii'}^{\tau}\right) + \sum_{i\in R} (b_i + \bar{\beta}_i^t) q_{ia}^t \left(1 - \sum_{\tau=1}^{t} y_{ii'}^{\tau}\right)\right) - b_a, \qquad \forall t \in T$$

excess supply is demanded

$$\bar{\beta}_i^{t+1} = \sum_{\tau=1}^{t} \beta_i^t \qquad \forall i \in E,\, t \in T$$

accumulated supply

$$\beta_i^t = \sum_{j\in E} \mathbf{1}_{j\in N_i} \beta_{ji}^t \qquad \forall i \in E \cup \{a\},\, t \in T$$

supply increase at node i

$$\sum_{j\in E} \mathbf{1}_{j\in M_i} \beta_{ij}^t \le (|b_i| + \bar{\beta}_i^t)\rho_i y_{ii'}^t \qquad \forall i \in E,\, t \in T$$

where node i can send supply

Trafficker Recruitment Rules

$$\sum_{i\in R_a} [\text{risk of } i] \times q_{ia}^t \le D_t, \qquad \forall t \in T$$

recruitment budget

$$\sum_{t=1}^{T} q_{ia}^t \le 1, \qquad \forall i \in R$$

recruit once

$$\sum_{t=1}^{t'_{ia}} p_{ia}^{\tau} = 0, \qquad \forall i \in R$$

cannot work before t' rounds

$$p_{ia}^{\tau} \ge q_{ia}^t \wedge \tau \ge t + t'_{ia} \qquad \forall i \in R,\, \forall t \in T$$

recruit working after t' rounds

$$p_{ia}^t \le \sum_{\tau=1}^{T} \mathbf{1}\{\tau + t'_{ia} \le t\} q_{ia}^{\tau}, \qquad \forall i \in R,\, t \in T$$

must wait t' rounds

$$\sum_{j\in E} \mathbf{1}_{j\in M_i} \beta_{ij}^t \le M \sum_{\tau=1}^{t} q_{ia}^{\tau}, \qquad \forall i \in R,\, t \in T$$

cannot send supply if not recruited

$$x_{ia}^t \le p_{ia}^t M, \qquad \forall i \in R,\, t \in T$$

sending capacity after t' rounds

Trafficker Variable Domains

$$q_{ia}^t \in \{0,1\}, \qquad \forall i \in R,\, t \in T$$

trafficker a recruits victim i at time t

$$p_{ia}^t \in \{0,1\}, \qquad \forall i \in R,\, t \in T$$

recruit i for trafficker a able to work at t

$$x_{ij}^t \ge 0, \qquad \forall (i,j) \in A,\, t \in T$$

flow on arc (i,j) at time t

$$u_i^t \ge 0, \qquad \forall i \in N,\, t \in T$$

production at node i at time t

$$\beta_i^t \ge 0, \qquad \forall i \in E,\, t \in T$$

supply shift at time t

$$\bar{\beta}_i^t \ge 0, \qquad \forall i \in E \cup \{a\},\, t \in T$$

accumulated supply shift at time t

$$\beta_{ji}^t \ge 0,\ i \ne j, \qquad \forall i,j \in E,\, t \in T$$

supply shift from j to i

Interdictor Variable Domain and Constraints

$$y_{ii'}^t \in \{0,1\}, \qquad \forall (i,i') \in A^E,\, t \in T$$

victim i interdiction decision

$$\sum_{(i,i')\in A^E} r_{ii'} y_{ii'}^t \le \mathcal{B}_t, \qquad \forall t \in T$$

interdiction budget

$$\sum_{t=1}^{T} y_{ii'}^t \le 1, \qquad \forall (i,i') \in A^E$$

interdict once

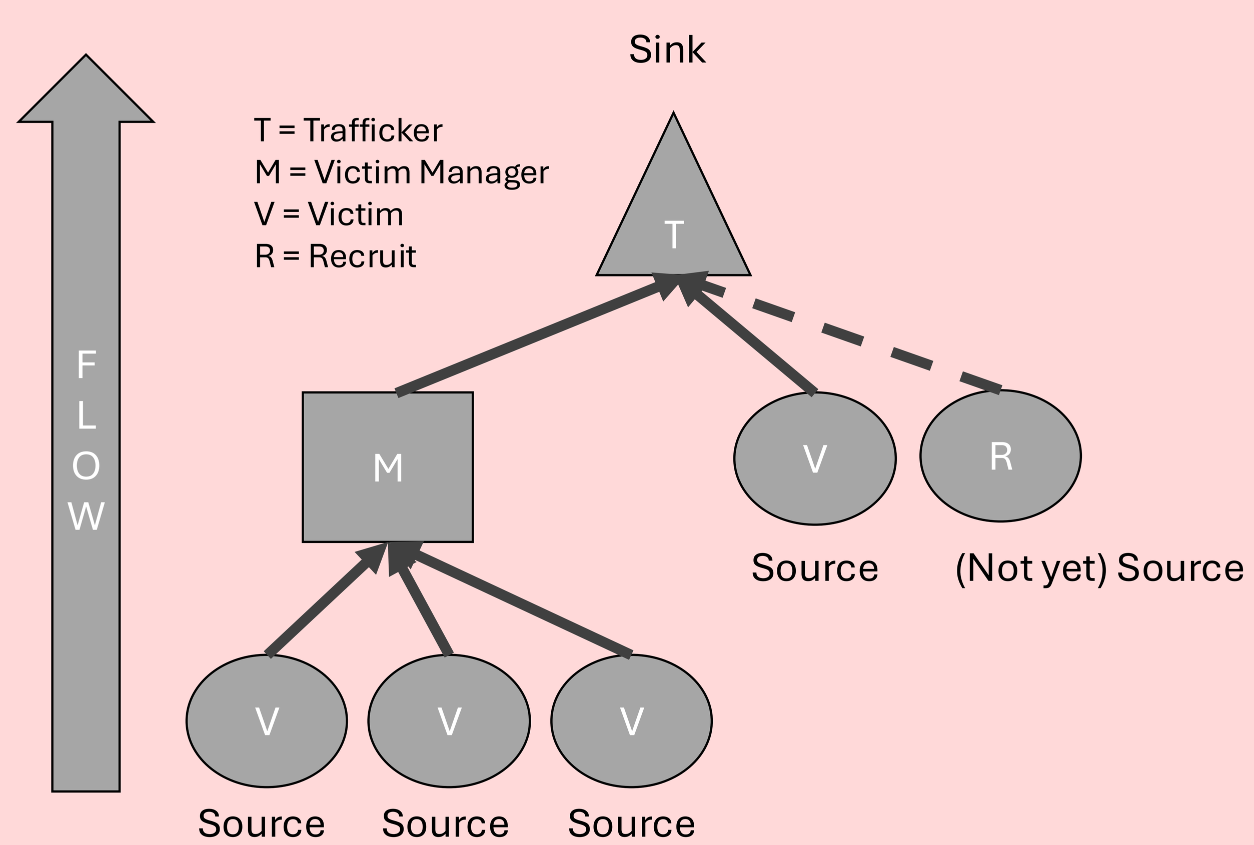
At each time step, 3 distinct moves are made

- **Move 1:** Interdictor takes action (help victims leave)
- **Move 2:** Trafficker minimum cost flow (MCF) computed (revenue generated)
- **Move 3:** Shift supply + capacity and recruitment activity for the next round (prepare for next round)

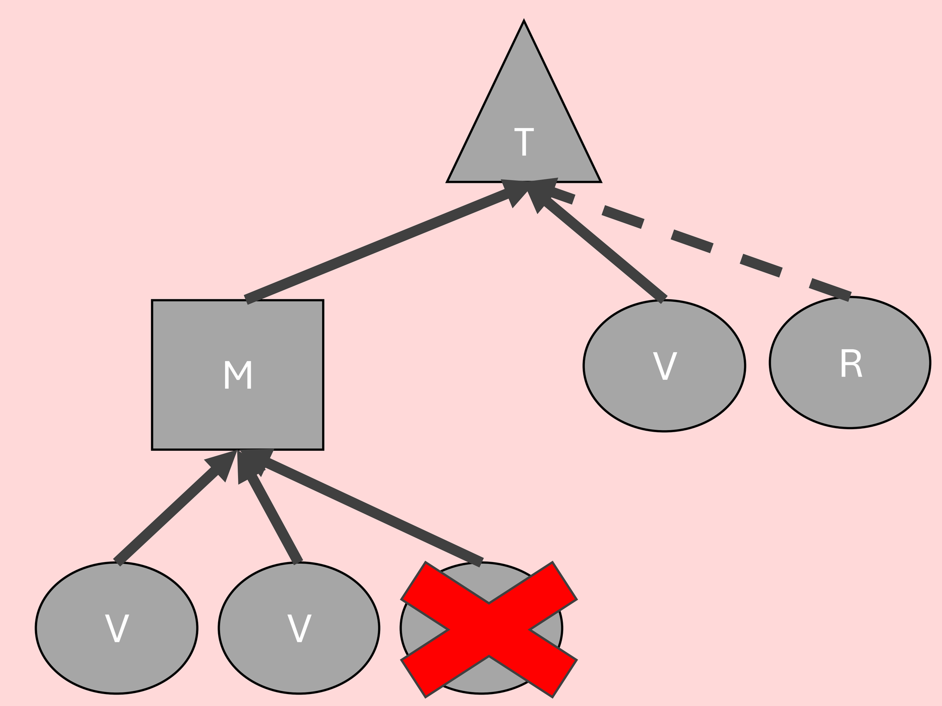
Goal: Provide decision-support to anti-trafficking organizations regarding how to optimally interdict human trafficking networks, while accounting for traffickers adjusting after interdiction.

- Traffickers seek to exploit victims (supply) for their gain (revenues)
- Victims have limited supply (e.g., exploited labor, sex, ...) to meet the trafficker's demand
- There is a risk (cost) and limitations (capacities) to how much the victims supply per day
- A *human trafficking network* acts like a supply chain

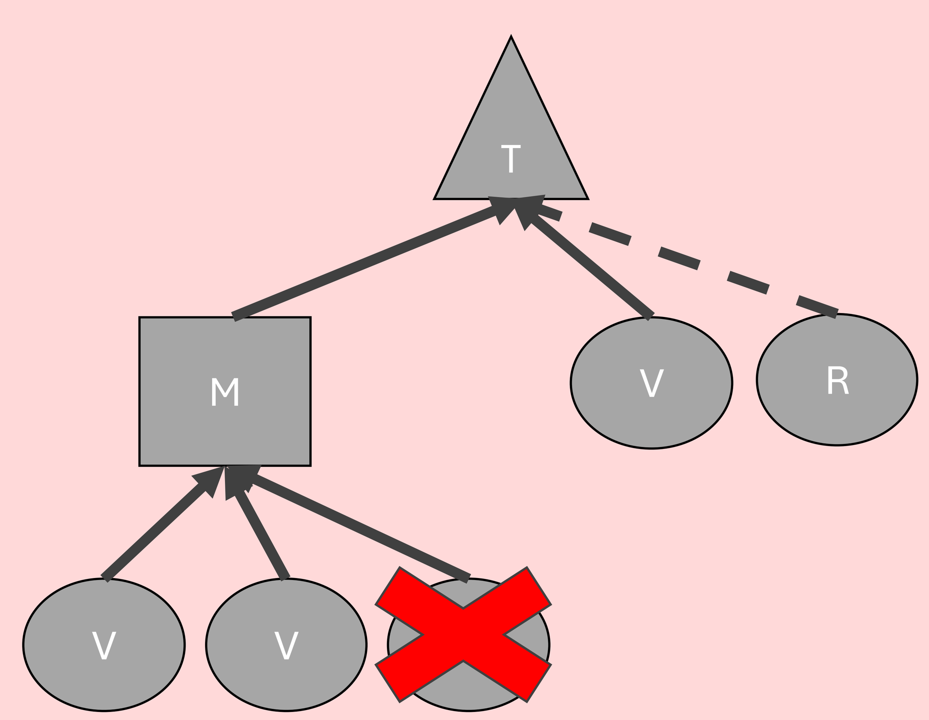
Network Overview



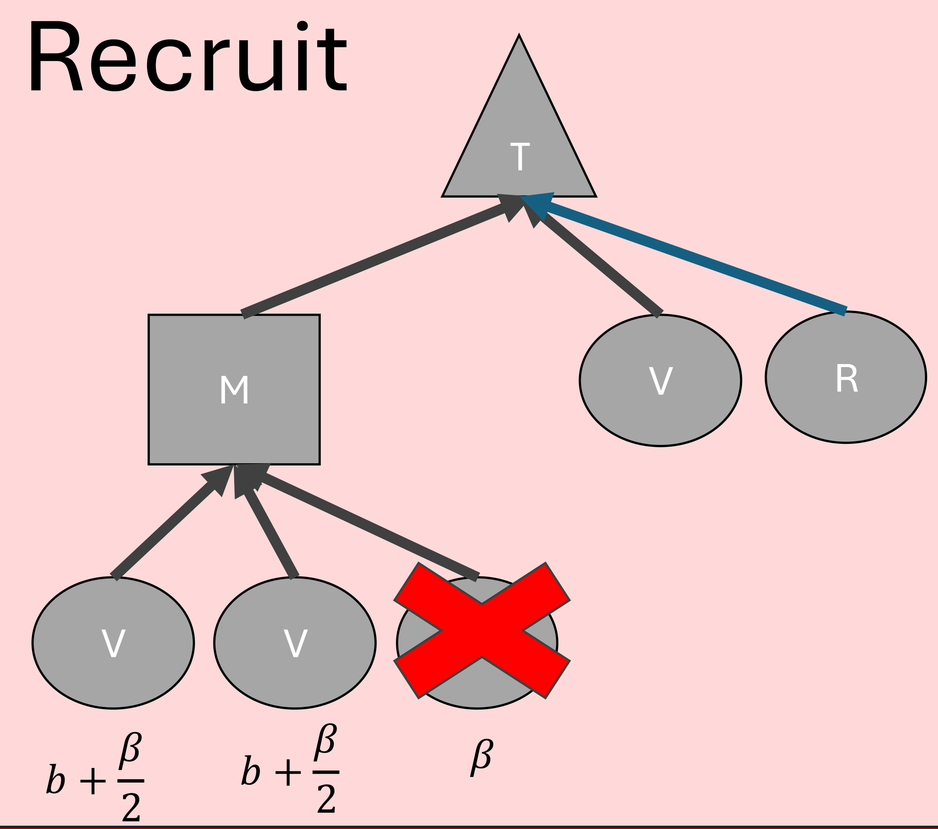
Move 1: Interdict



Move 2: MCF



Move 3: Shift & Recruit



By accounting for recruitment and supply shifting that more realistically captures the consequences of interdiction, we can more accurately provide interdiction recommendations for better decision making!

Solution Methodology:
Column and Constraint Generation (CCG)

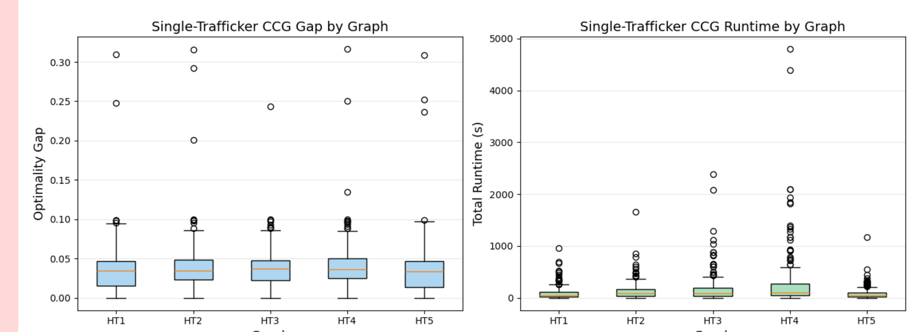
- Iteratively obtain upper and lower bounds through solving master and subproblems
- The master problem determines an optimal interdiction under a subset of scenarios
- Terminate when below relative optimality threshold

Numerical Experiments

- Two types of networks:
  - Synthetic, yet realistic networks
  - Fully synthetically generated
- Gurobi 12 for MILP solver

Parameters

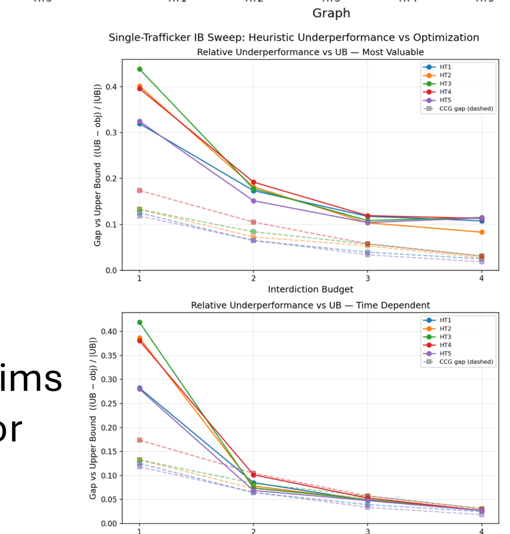
- Interdict cost:
  - Victims and recruits: 1
  - Victim Manager: 3
- Random integer supply for victims
- Flow costs
  - Victim → Trafficker: 1
  - Victim Manager → Trafficker: 2
  - Restructured Victim → Trafficker: 10
- Each network has ~ 10 people



Heuristics:

Heuristics from practice perform comparably!

Most valuable victims (Time dependent or independent)



Insights

- Victim managers are interdicted towards the end of the time horizons
- CCG Methods uncover nongreedy interdiction patterns
- Symmetric data makes CCG significantly more challenging

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