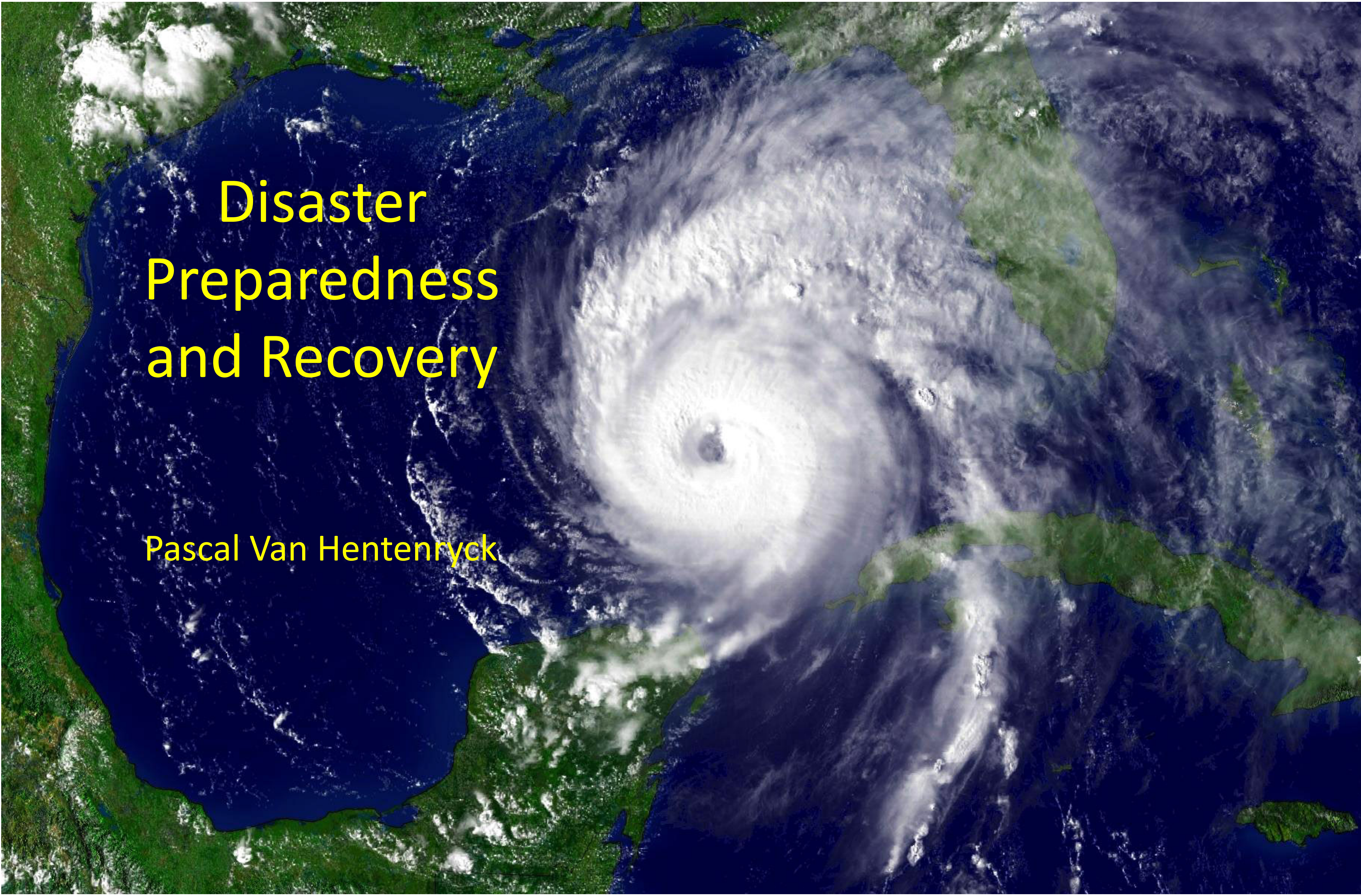

Disaster Preparedness and Recovery

Pascal Van Hentenryck

Outline

- Motivation
- Disaster preparedness & recovery for a single commodity
  - *CPAIOR-10, CPAIOR-11*
- Last mile recovery of electrical power systems
  - *17th Power Systems Computation Conference (PSCC'11)*
- *Strategic stockpiling of power supplies for disaster recovery*
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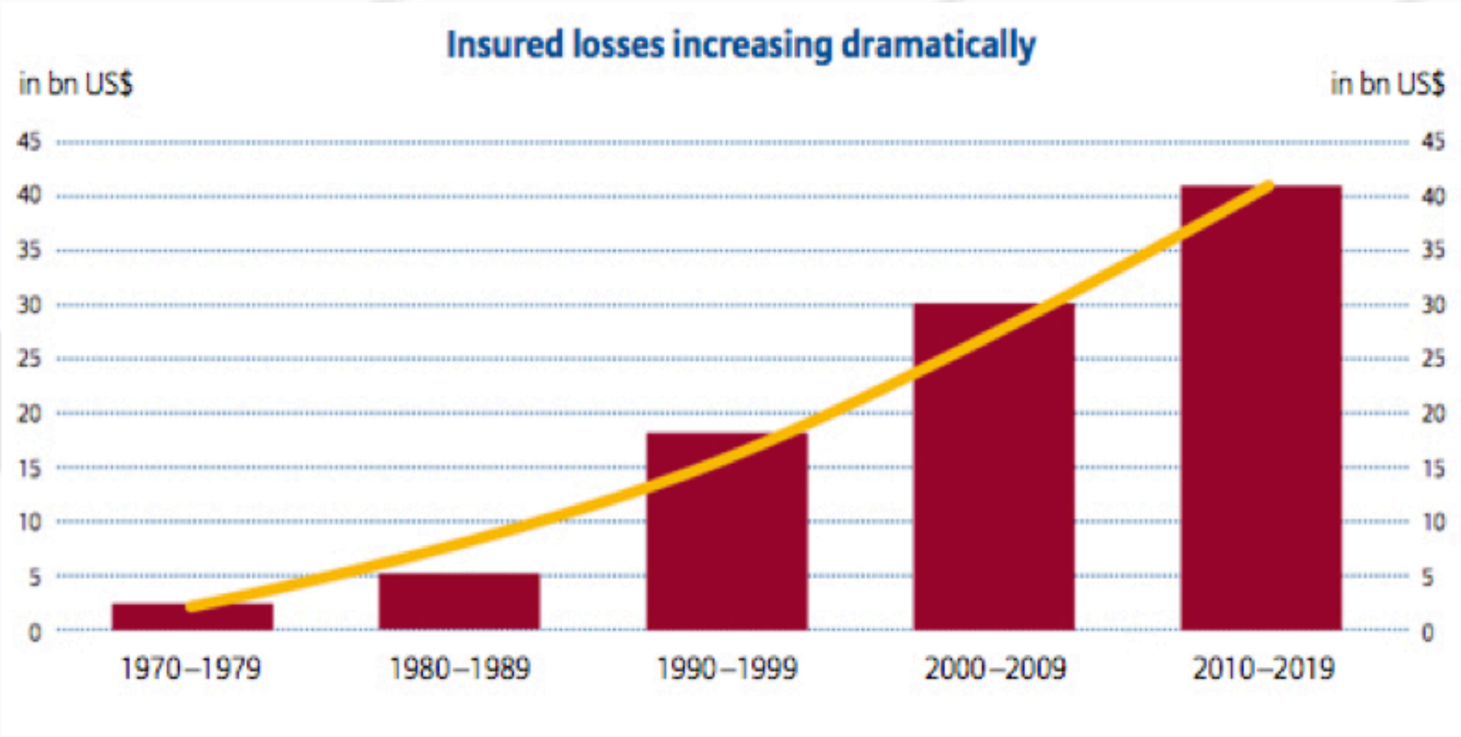
- Conclusion and Future Work

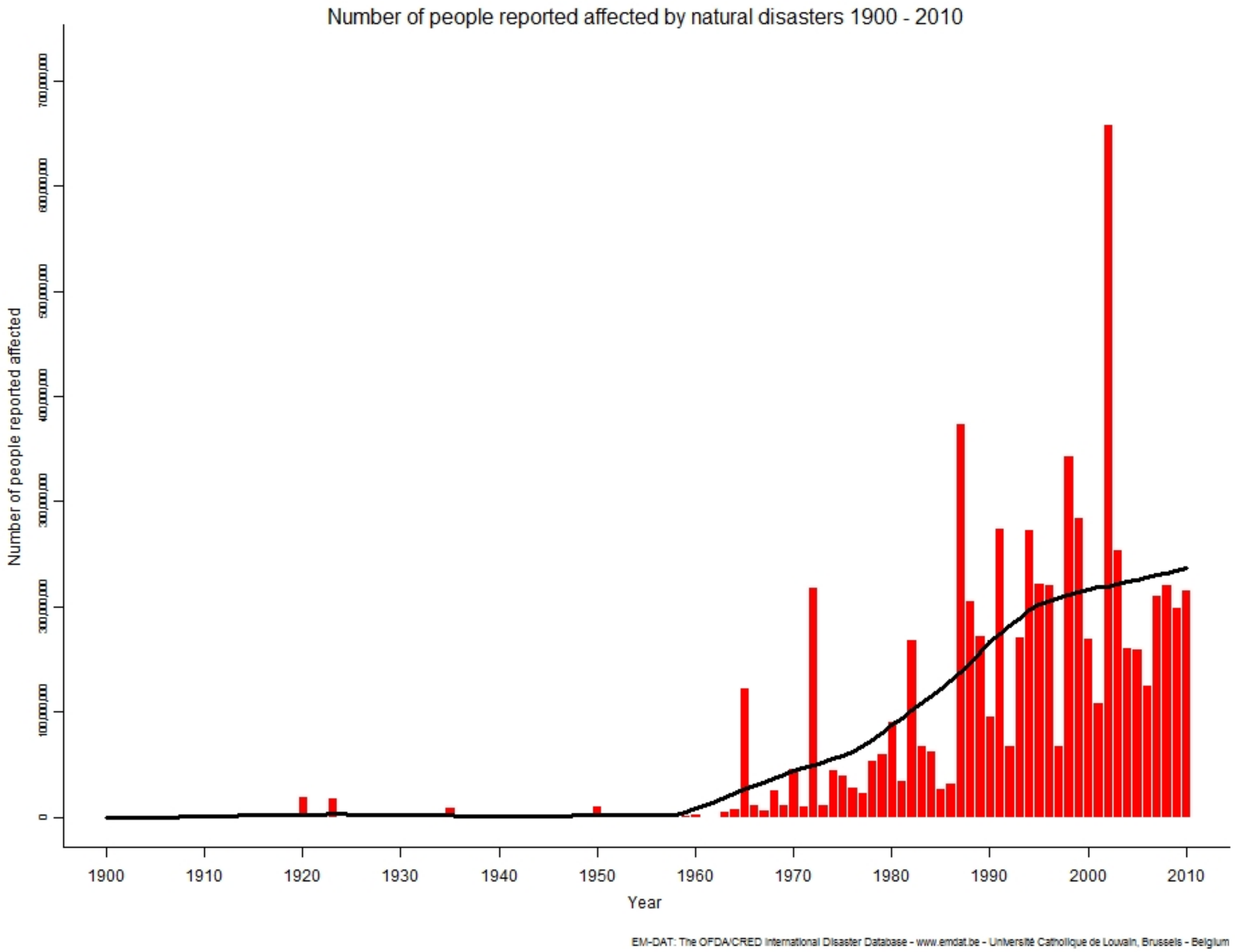
(Joint work with C. Carleton and R. Bent)

The Rising Cost of Disasters

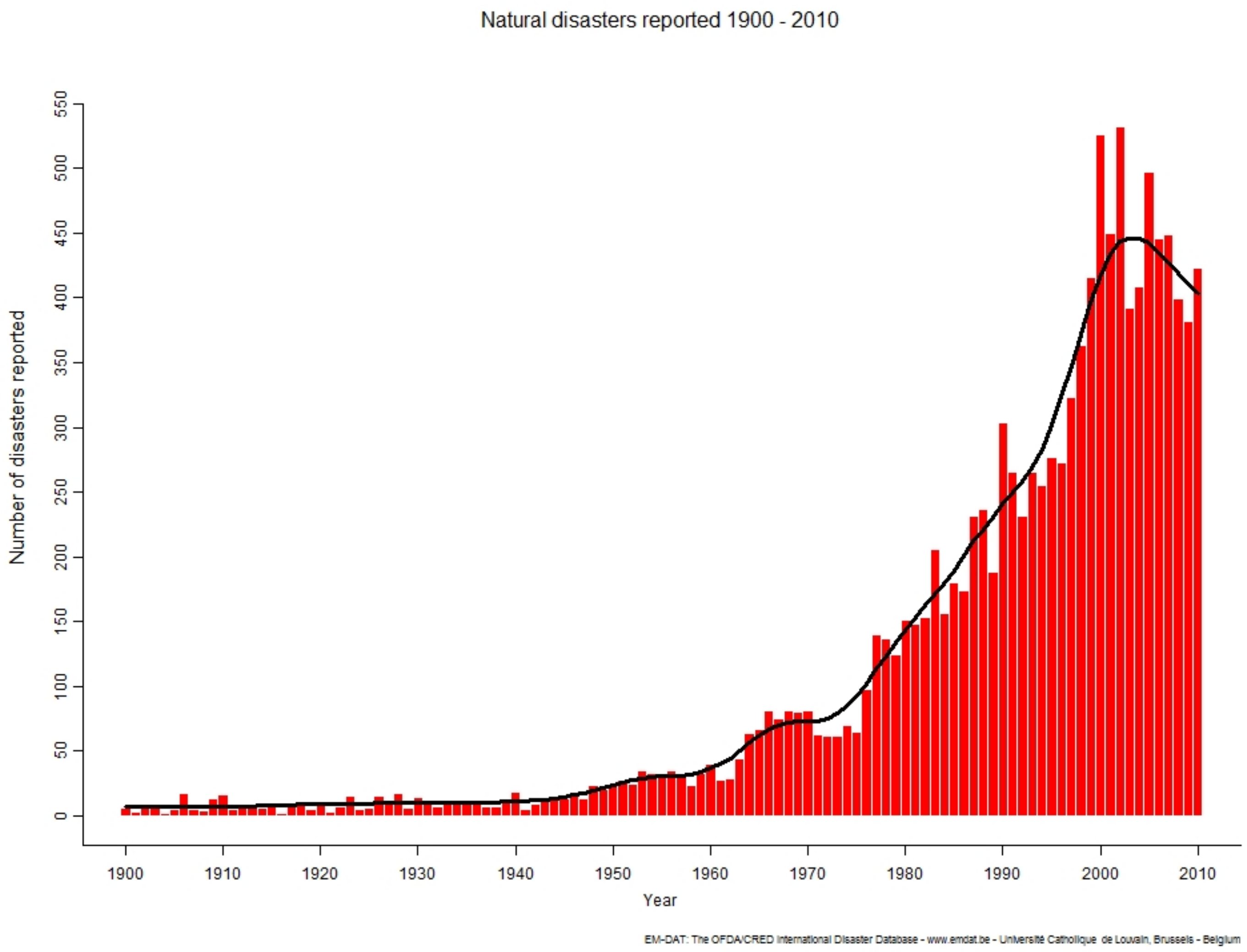


(Jared Wade: Risk Management, 2011)

The Rising Costs of Disasters



The Rising Cost of Disasters



2011 Predictions

- “72% chance that at least one major hurricane will make landfall on the U.S. coastline in 2011 (the long-term average probability is 52%)”
- “A 48% chance that a major hurricane will make landfall on the U.S. East Coast, including the Florida Peninsula (the long-term average is 31%)”
- “A 47% chance that a major hurricane will make landfall on the Gulf Coast from the Florida Panhandle west to Brownsville (the long-term average is 30%)”

(Emily Holbrook: 2011 Hurricane Predictions, Risk Management, 2001)

Disaster Preparedness and Recovery (DPR)

- *``Much of it is telecommunications, but it's really about how you use a whole bunch of things so that you are able to manage the resources for medicine, power, water and all the 20 or so major things that you need to do in the wake of a disaster.''*

Eric Frost, veteran of the tsunami relief

Disaster Preparedness and Recovery (DPR)

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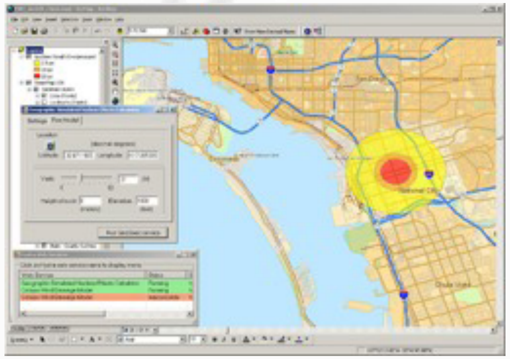
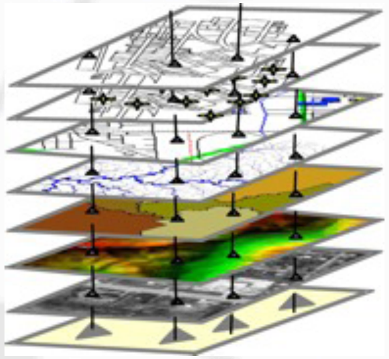
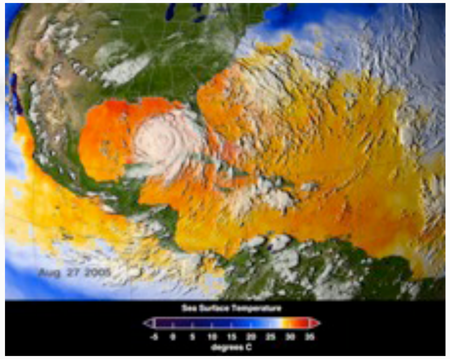
  Eric Frost, veteran of the tsunami relief

- *``We don't need a donors' conference,*
  we need a logistics conference''

  European Ambassador at post-Tsunami donor conference,
  New York Times, Jan 6, 2005

Collaboration with DHS and LANL

- The Department of Homeland Security (DHS) asked *"...to address critical infrastructure protection issues related to counterterrorism, threat assessment, and risk mitigation."*

- DHS asked LANL to provide with **"fast-response"** analysis and decision support when major disasters have occurred or are pending.

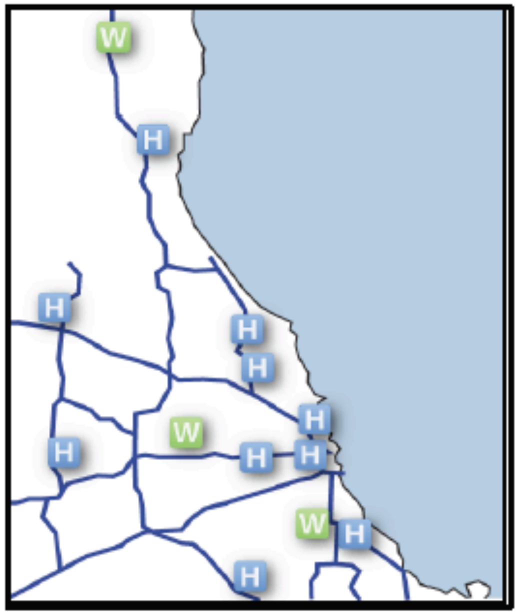
Humanitarian Logistics (I)

- Investigated since the early 1990s [Ergun, 2010]
- Significant complexity
  - Joint inventory, location, routing, simulation problems
  - Fast response time
  - Stochastic nature
    - Unpredictability of disasters [Duran, 08, Gunnec, 07,Keskinocak, 2009]
  - Non-standard objective functions
    - Makespan objective in vehicle routing [Barbarosoglu 02,Campbell 08]
    - Equitability objectives [Balcik, 08]
  - Multi-objective optimization
    - Balancing service, budget, response time [Balcik, 08, Barbarosoglu 02, Gunnec, 07]

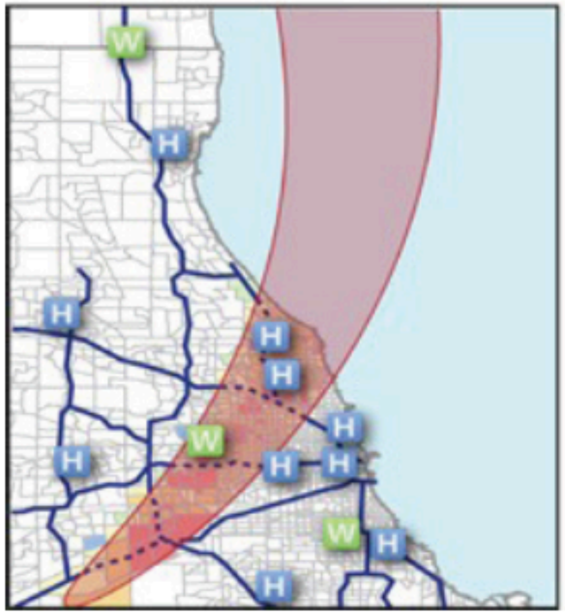
Humanitarian Logistics (II)

- Computational difficulties
  - Mixed Integer Programming (MIP) solvers have difficulties with these features [Balcik 08, Barbarosoglu 02, Gunes 10]
    - even for some small instances [Campbell 08]
  - Evaluating the objective function may be highly complex
    - generalization of Optimal Transmission Switching [Ferris 08]
- Different time scales
  - Weeks [Duran, 08], Minutes [Balcik 08, Gunes 10]
- This work: Last-Mile Distribution (city or state scale)
  - First last-mile humanitarian logistic application taking into account stochastic, location, routing, and simulation aspects

Disaster Preparedness: Inputs



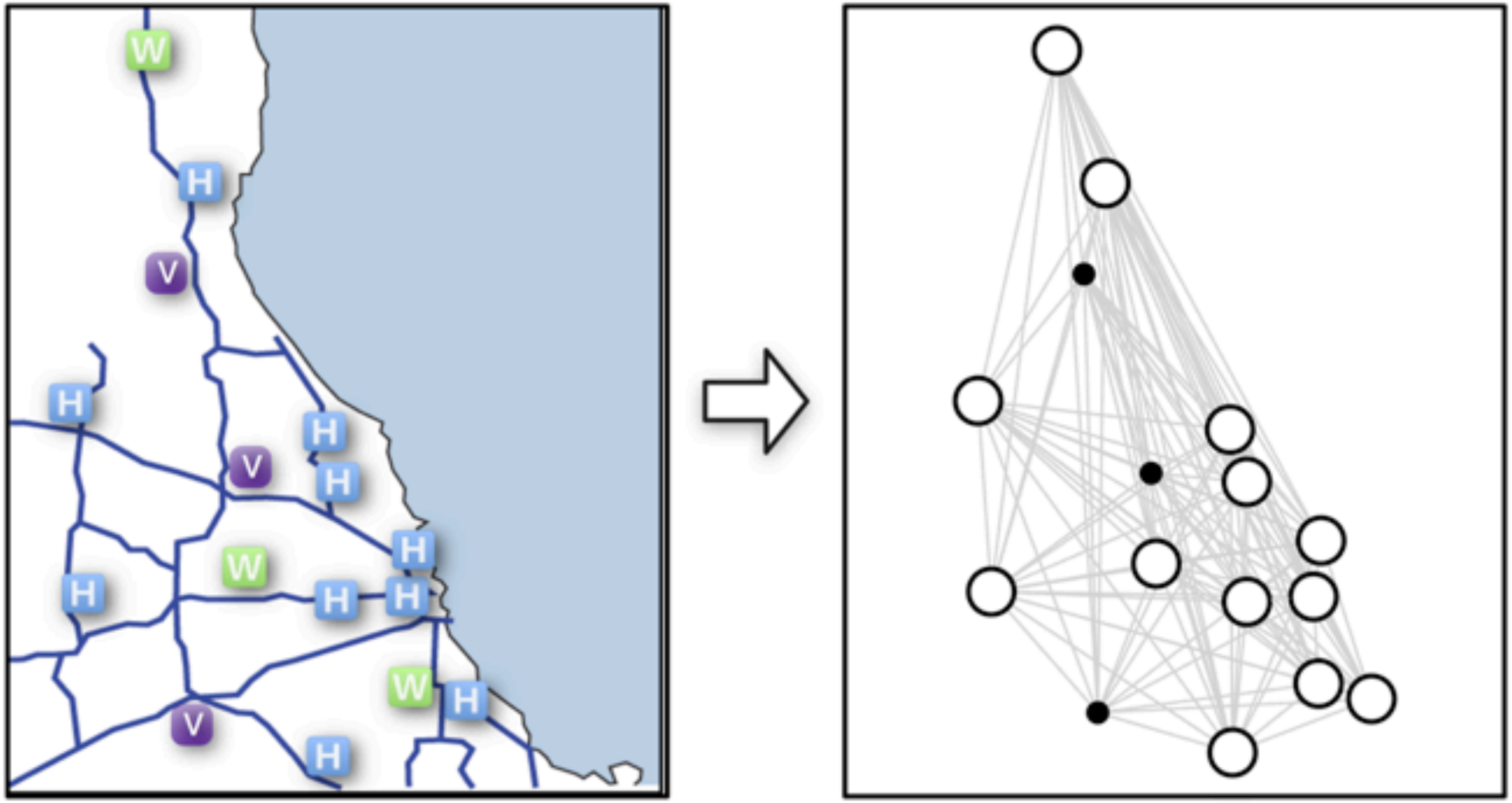
Infrastructure

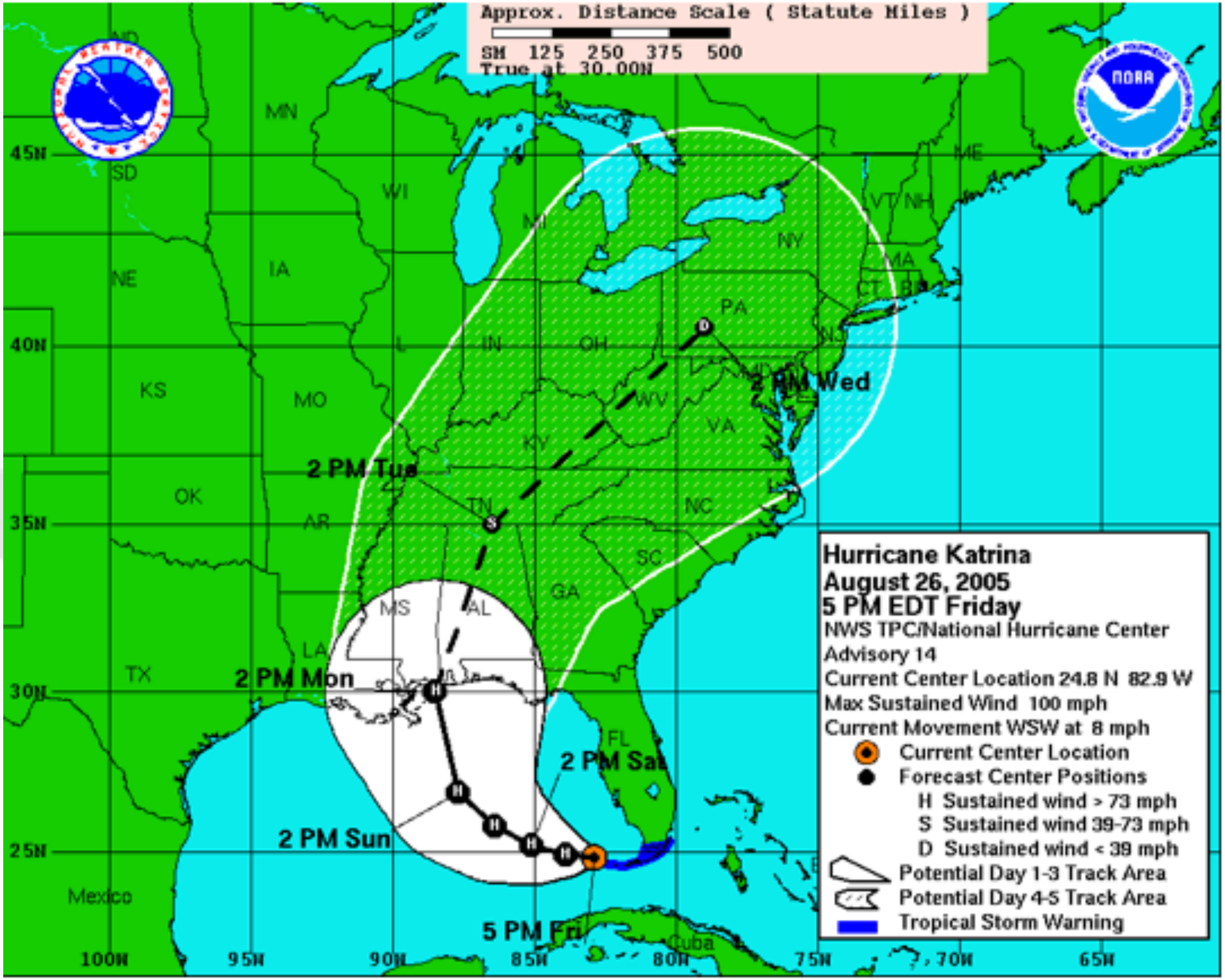


Tracks
(Weather Simulation)

Damages
(Fragility Simulation)

Infrastructure Abstraction

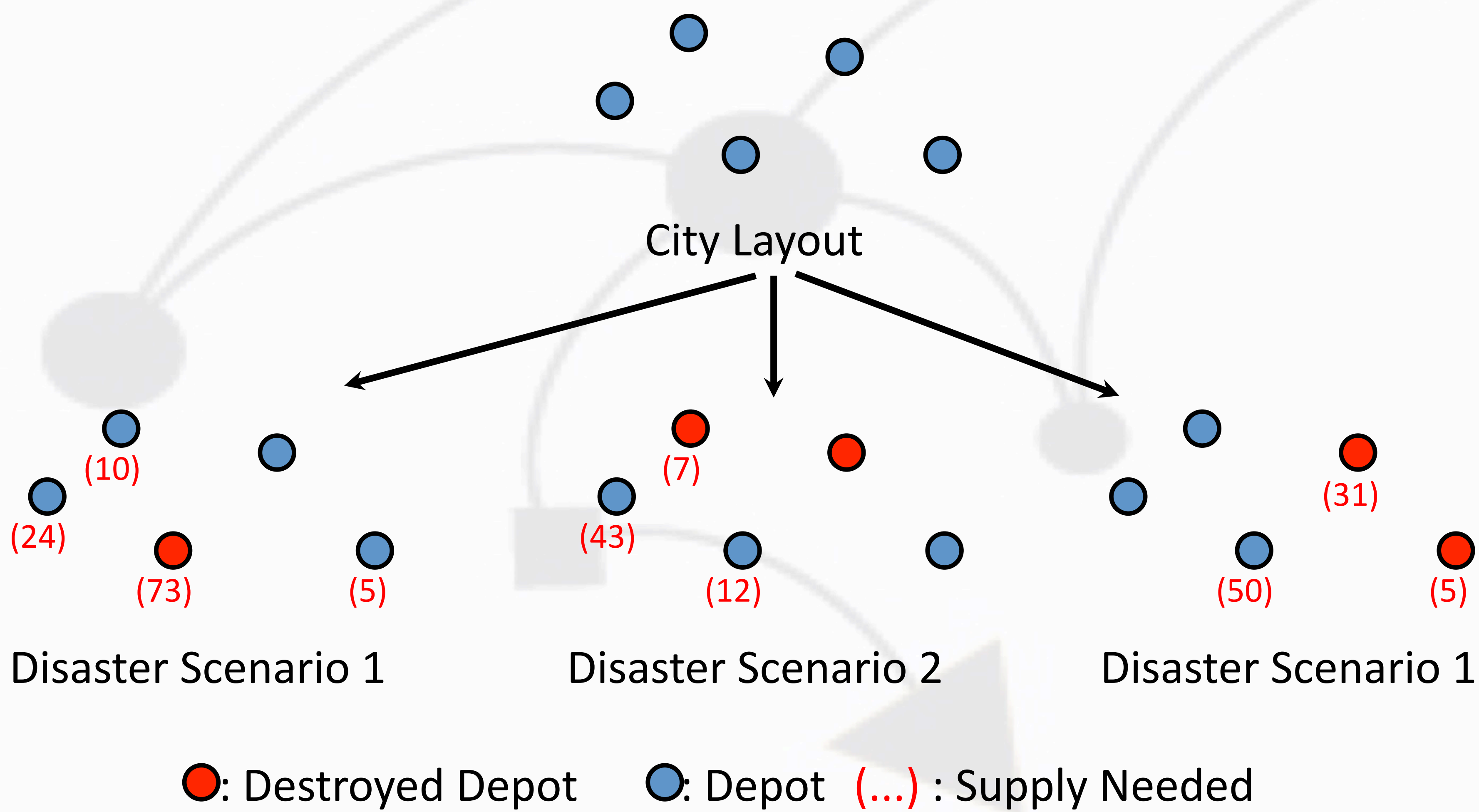




Approx. Distance Scale (Statute Miles)
SM 125 250 375 500
True at 30.00N
Hurricane Katrina
August 26, 2005
5 PM EDT Friday
NWS TPC/National Hurricane Center
Advisory 14
Current Center Location 24.8 N 82.9 W
Max Sustained Wind 100 mph
Current Movement WSW at 8 mph
Current Center Location
Forecast Center Positions
H Sustained wind > 73 mph
S Sustained wind 39-73 mph
D Sustained wind < 39 mph
Potential Day 1-3 Track Area
Potential Day 4-5 Track Area
Tropical Storm Warning
2 PM Wed
2 PM Tue
2 PM Mon
2 PM Sun
2 PM Sat
5 PM Fri
45N
40N
35N
30N
25N
100W
95W
90W
85W
80W
75W
70W
65W
MN
WI
MI
SD
NE
IA
KS
MO
OK
AR
TX
LA
MS
AL
TN
KY
GA
SC
NC
VA
WV
OH
IN
PA
NY
NJ
ME
VT
NH
MA
CT
FL
Mexico
Cuba

Disaster Prediction

Explicit Scenarios



Disaster Preparedness and Recovery

- Two main steps
  - Planning: before the disaster
  - Response: after the disaster
- Planning before the disaster
  - Stockpiling resources to respond quickly and effectively
- Response and Recovery after the disaster
  - Responding and restoring the infrastructures

Some Disclaimers

- Computational complexity
  - Often impossible to obtain optimal solutions
- Empirical Methodology
  - Determine whether we can improve the practice in the field
  - Try to estimate the quality of the solutions
  - Try to identify the bottlenecks to drive technological progress
  - First attempt at the considered problems
- Organization of the talk
  - Give some ideas of the underlying technology
  - High-level presentation of various models
    - Papers available on all aspects

Demonstrations in Comet

- Comet system (about 750,000 lines of code)
  - Full-fledged object-oriented programming language
  - Advanced control features
    - closures and continuations, events and dynamic aspects
  - Advanced Search features
    - High-level nondeterministic instructions
  - Parallel programming features
    - parall loop, interruptions, thread/machine pools
- Optimization Solvers
  - Constraint programming, Local Search, MIP (more to come)

(Joint work with Laurent Michel)

Large Neighborhood Search

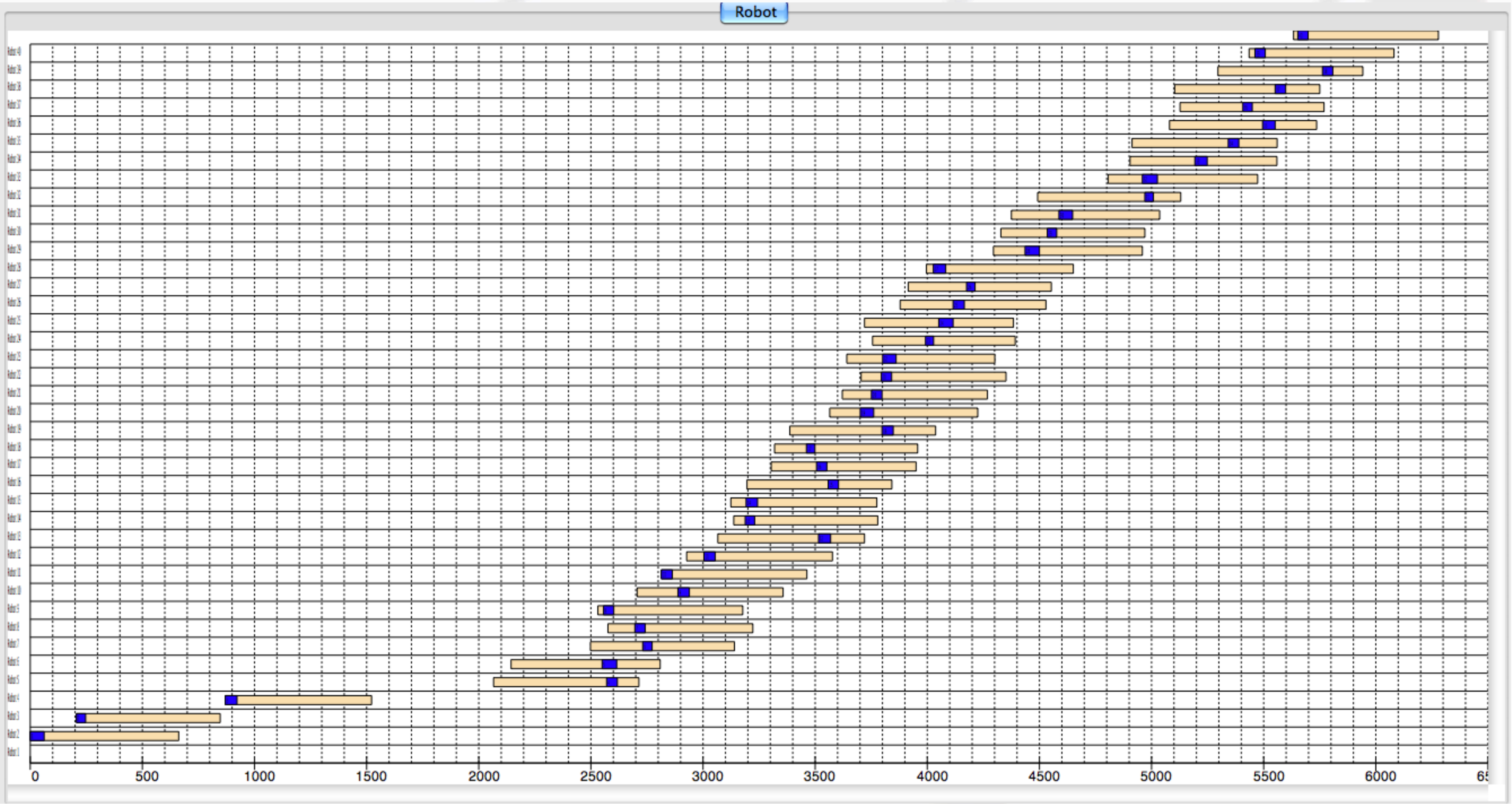
- Large Neighborhood Search
  - Combination of global and local search
- Start with a feasible solution
- Iterate two steps
  - Relax a part of the solution and fix the rest.
  - Reoptimize the relaxed part (not necessarily to optimality)
- Strengths
  - Explore large neighborhoods effectively
  - Scalability

Asymmetric TSP with Time Windows

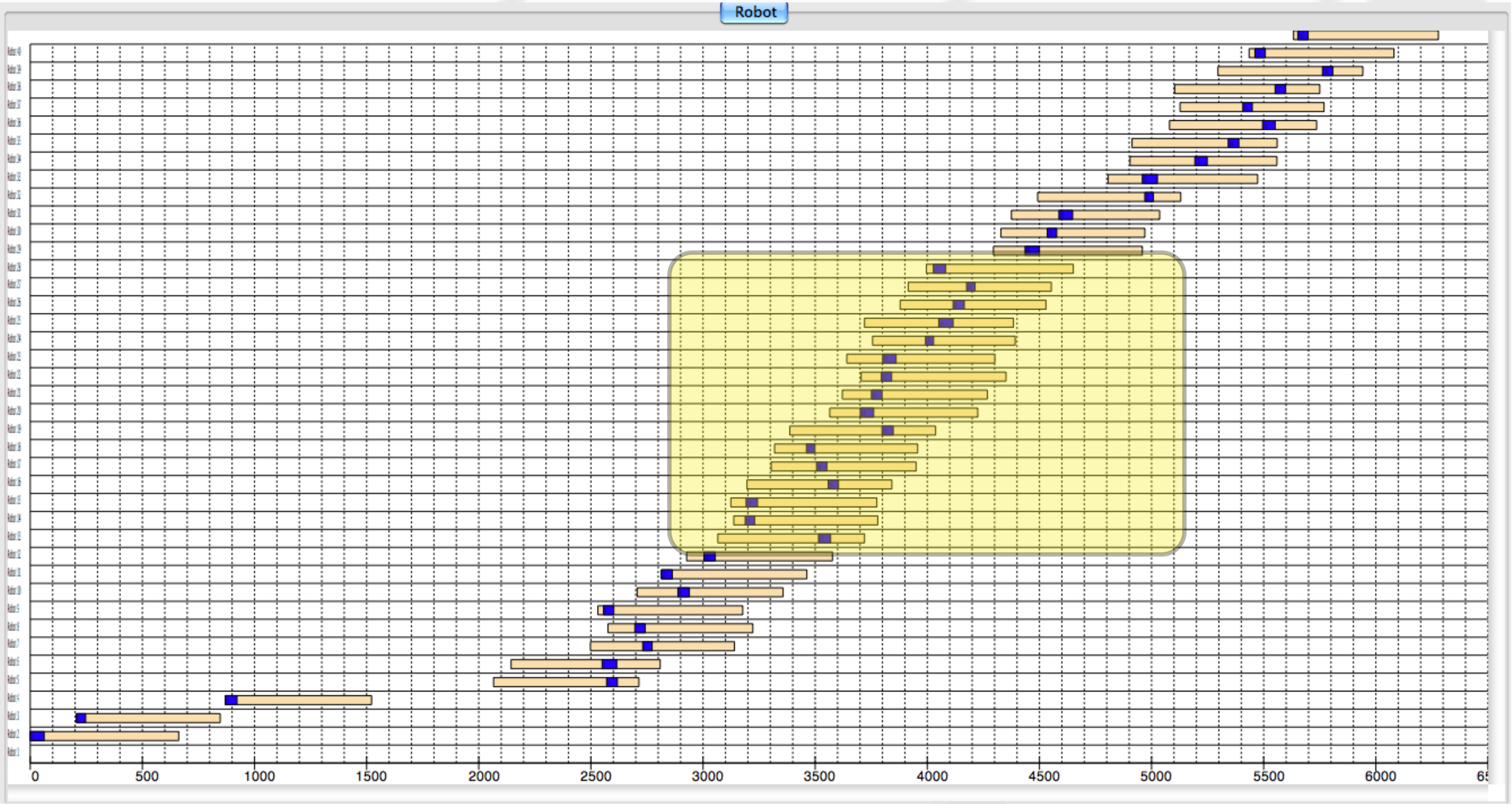
- The input: we are given
  - a set of locations to visit
  - a service time for each location
  - a time window when to serve a location
  - the (asymmetric) travel distance between locations
- the goal: find a hamiltonian path
  - satisfying the time windows
  - minimizing the travel distance

Tension

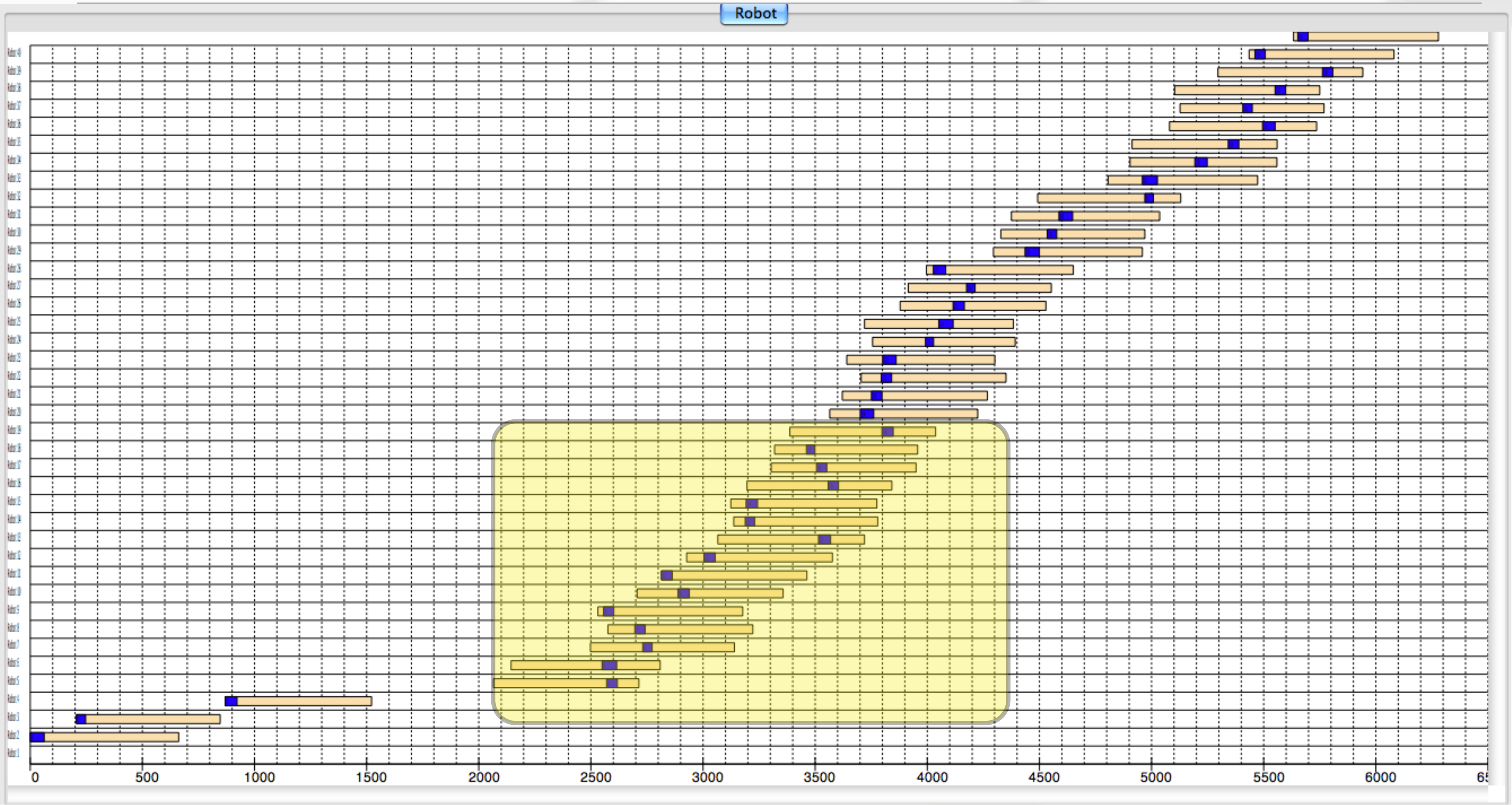
Asymmetric TSP with Time Windows



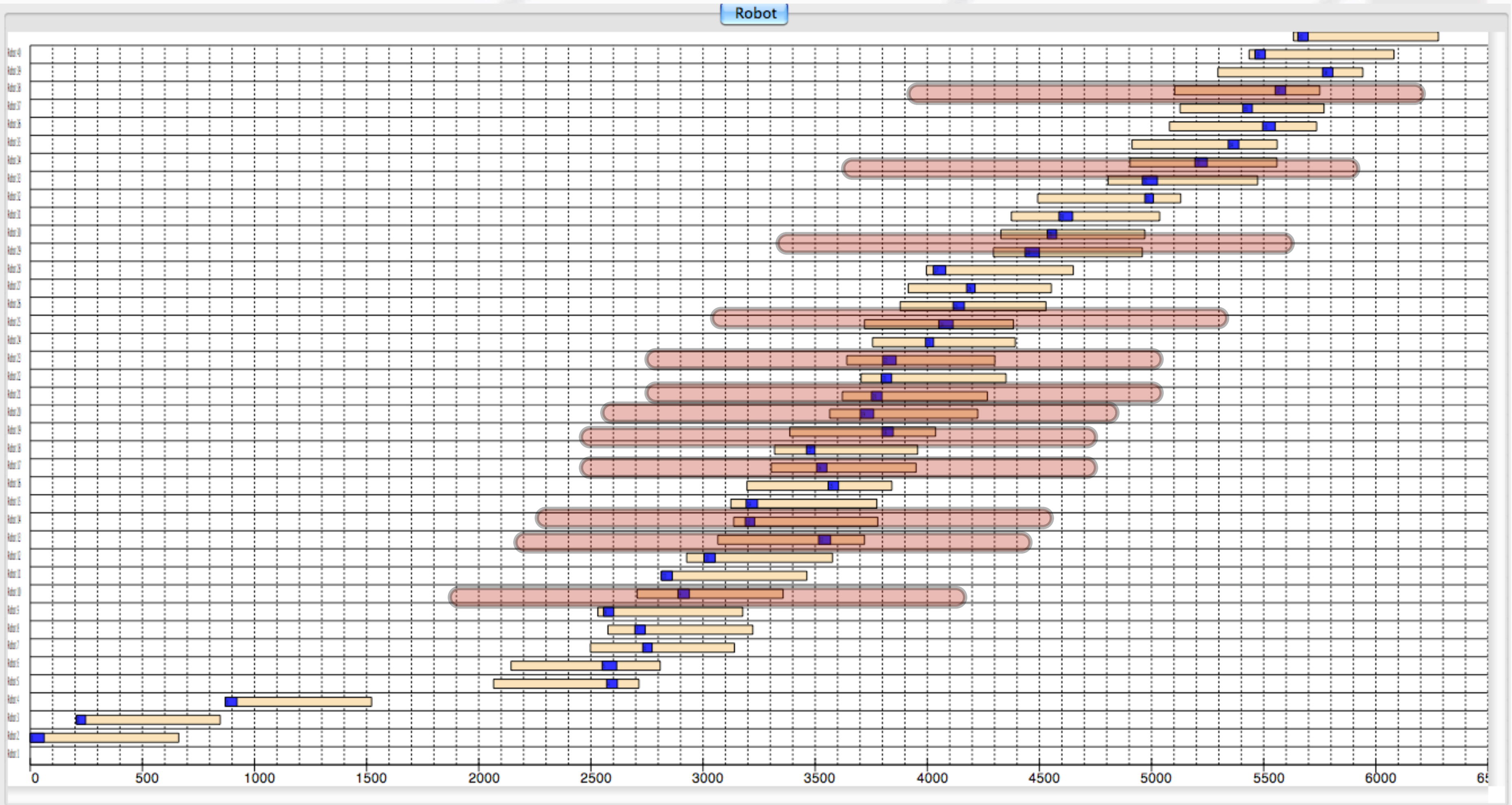
Asymmetric TSP with Time Windows



Asymmetric TSP with Time Windows



Asymmetric TSP with Time Windows



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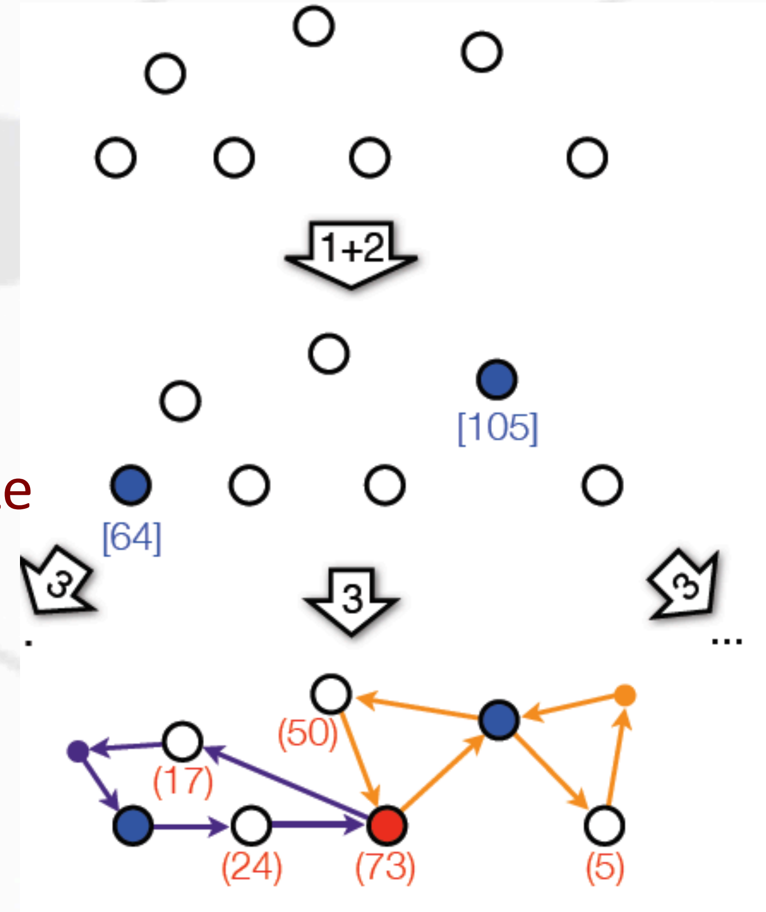
(Joint work with C. Carleton and R. Bent)

DPR for a Single Commodity

1. Where to store the supply?
2. How much supply to store?
3. Given a particular disaster, what is a fast delivery plan



Over all predicted disasters, minimize

1. Unsatisfied demand
2. Latest delivery time
3. Storage costs

DPR for a Single Commodity

- Too difficult to handle globally
  - 2-stage stochastic joint location, inventory, and routing
  - Simplified deterministic version is very hard [Prins 08]
- Routing objective
  - Minimize latest delivery (DHS requirement)
  - Challenging for MIP solvers even for small sizes [Campbell 08]
- Multiple trips needed per location
  - Demand exceeds the vehicle capacity
- Large scale:
  - Disasters for an entire state such as Florida

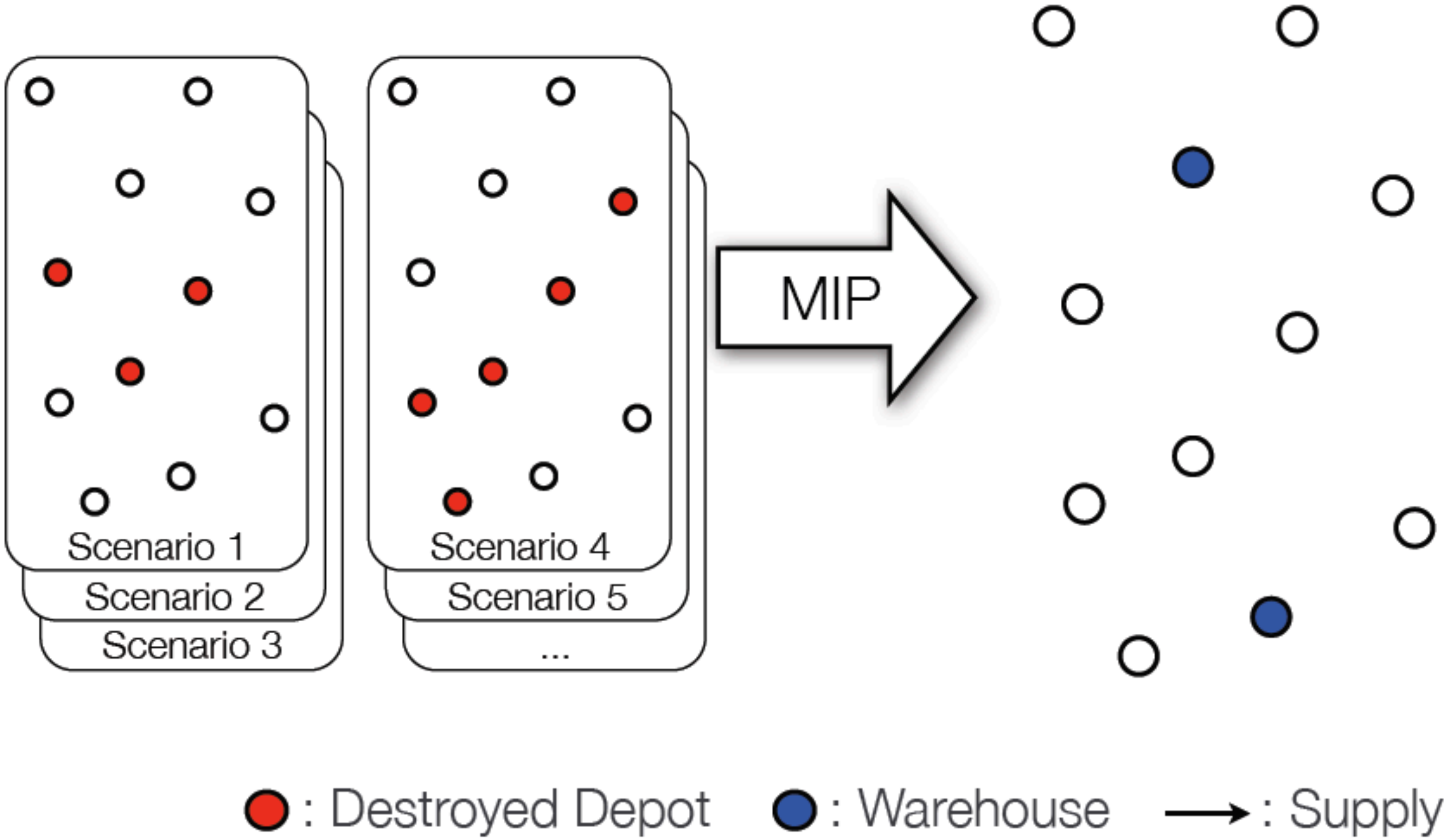
DPR for a Single Commodity

- Break into 4 sub-problems
  - Stochastic Warehouse allocation: MIP (to optimality)
    - where to store the commodity?
    - approximates the routing aspects
  - Customer allocation: MIP (to optimality)
    - Which warehouse supply which customers?
  - Repository routing: MIP or CP (to optimality)
    - How to serve the customers of a warehouses?
  - Fleet routing: LNS + CP
    - How to route all the vehicles globally?

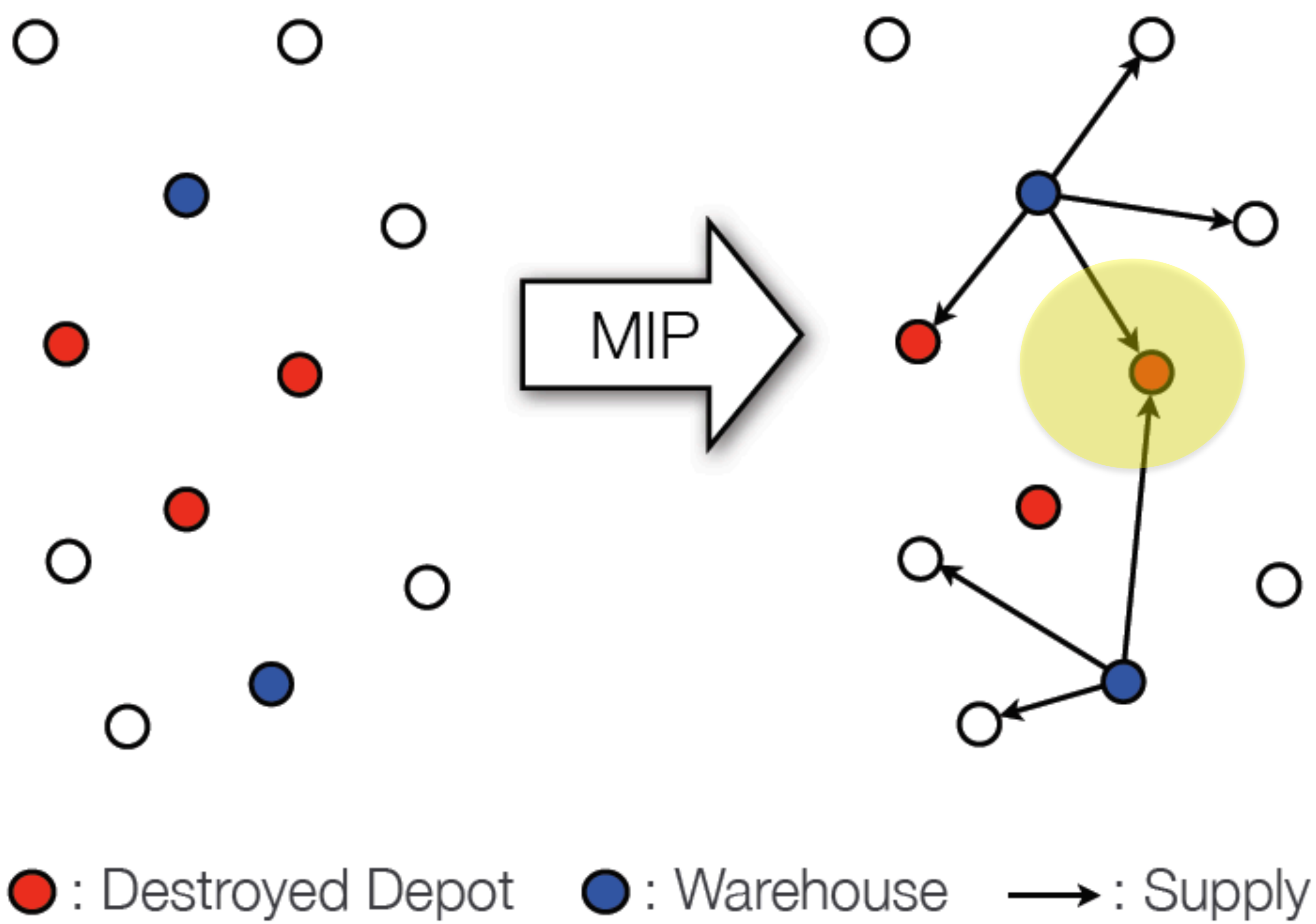
First Stage (Stochastic Warehouse allocation)

Second Stage (Customer allocation, Repository routing, Fleet routing)

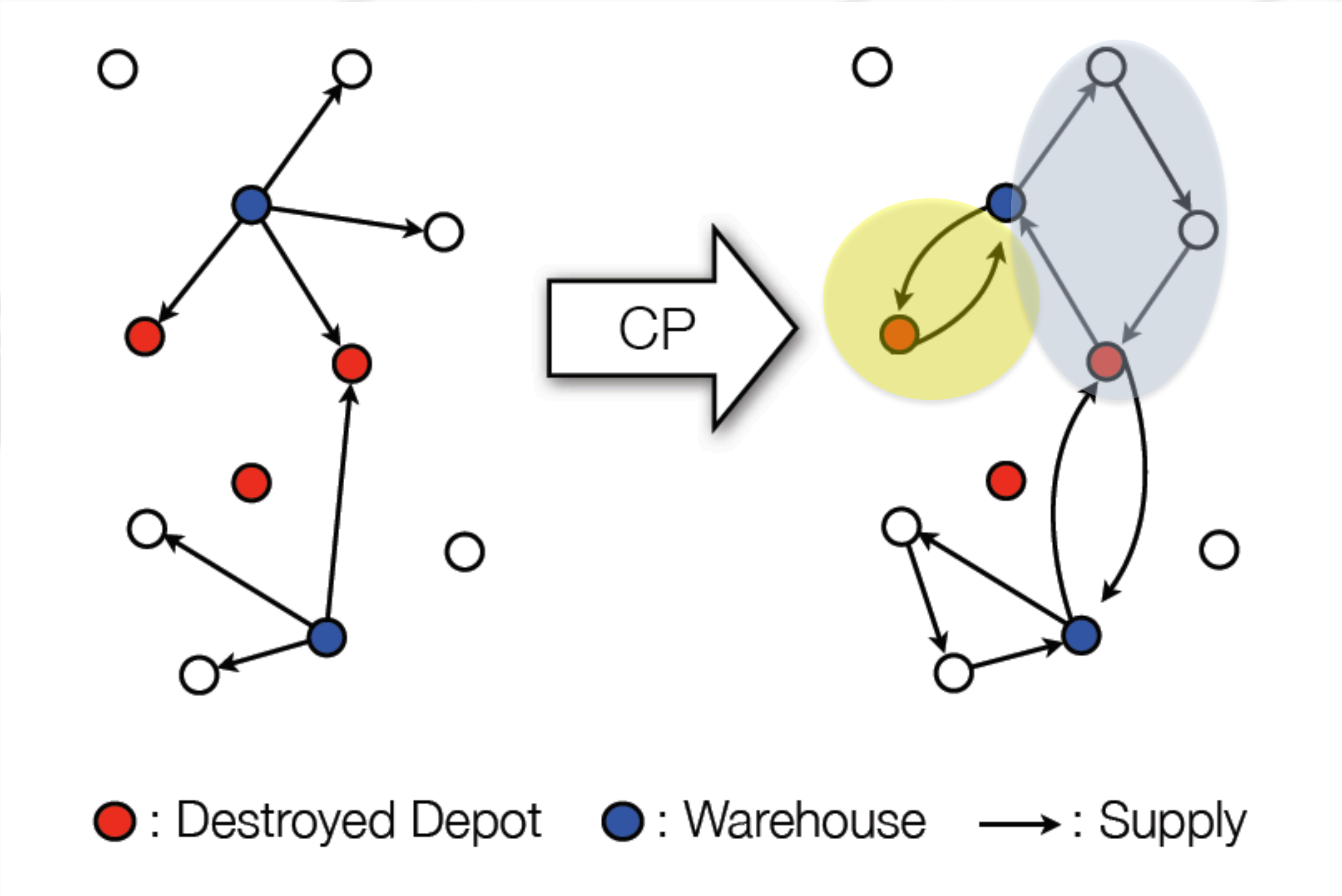
Stochastic Warehouse Location



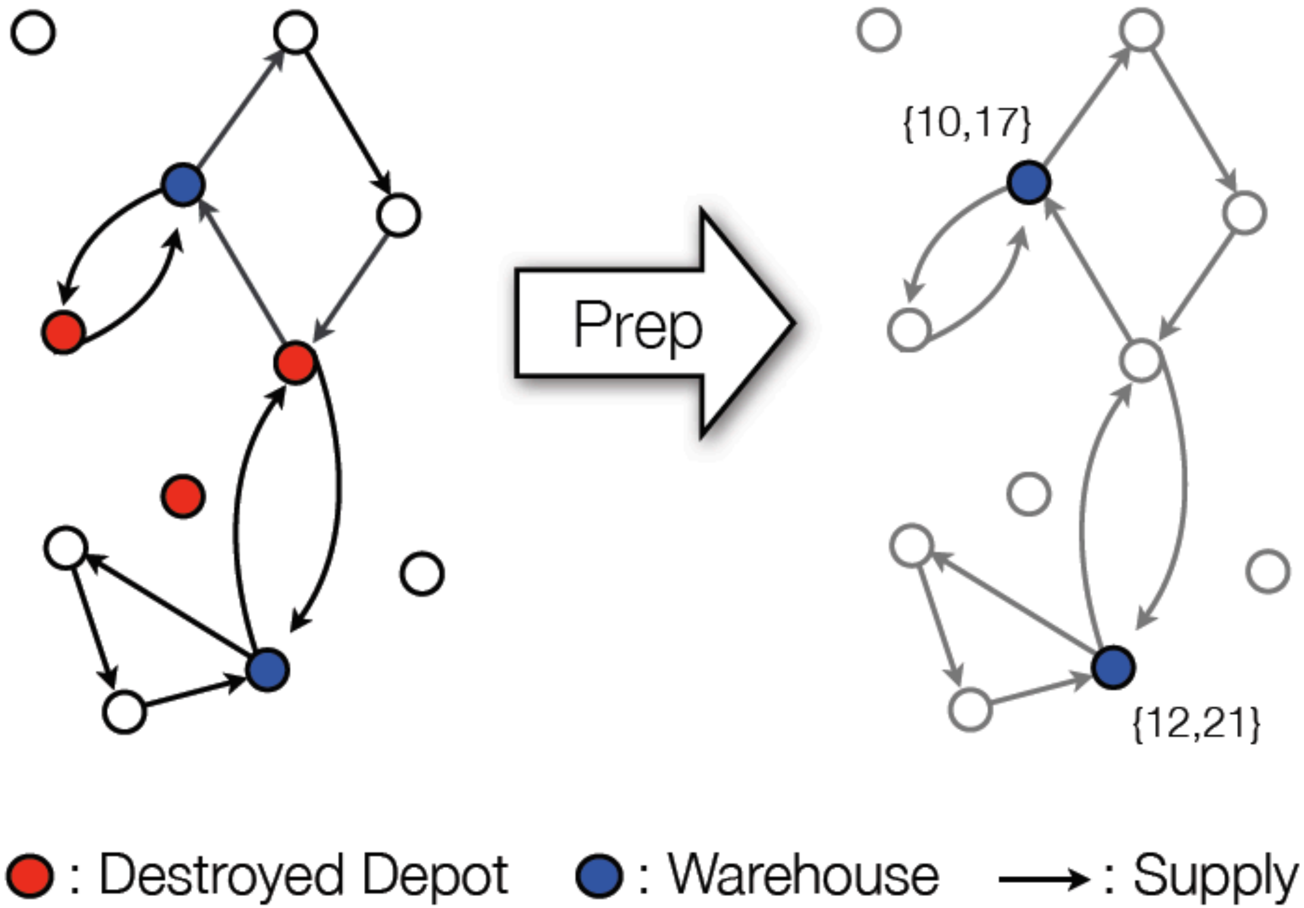
Customer Allocation



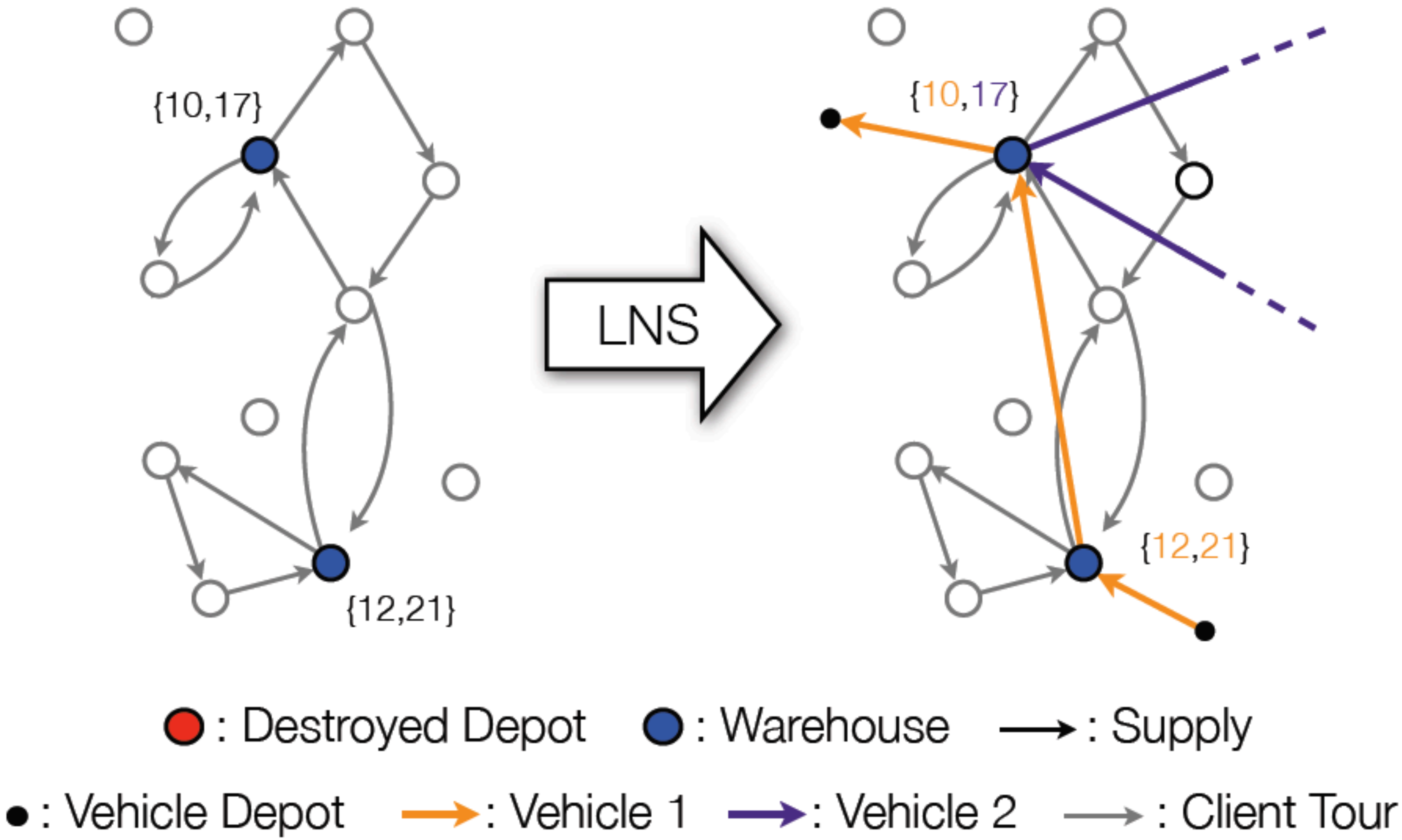
Repository Routing



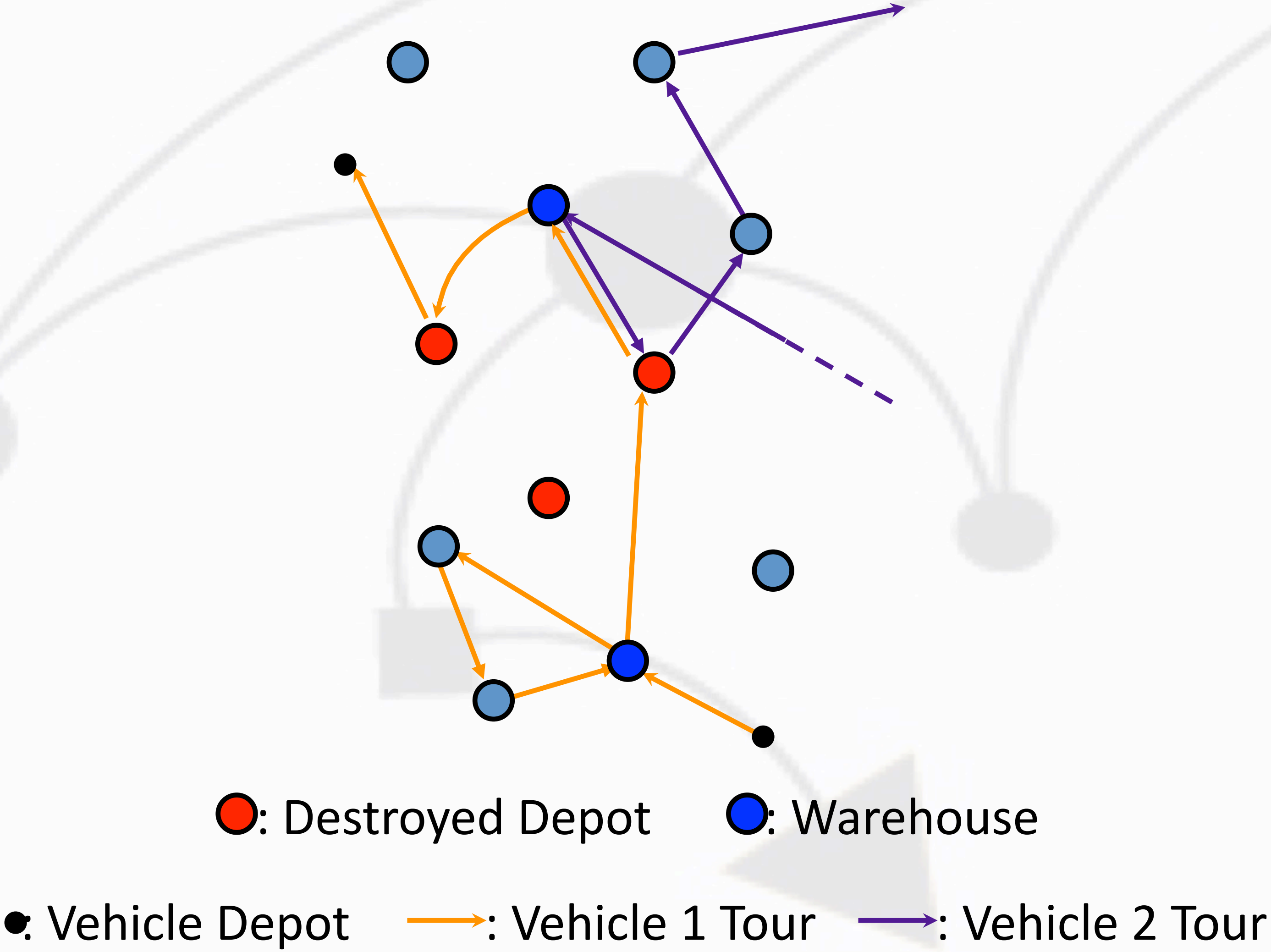
Post-Processing the Repository Routing



Fleet Routing



Output


: Destroyed Depot
: Warehouse
: Vehicle Depot
: Vehicle 1 Tour
: Vehicle 2 Tour

Experimental Results: Water Supply

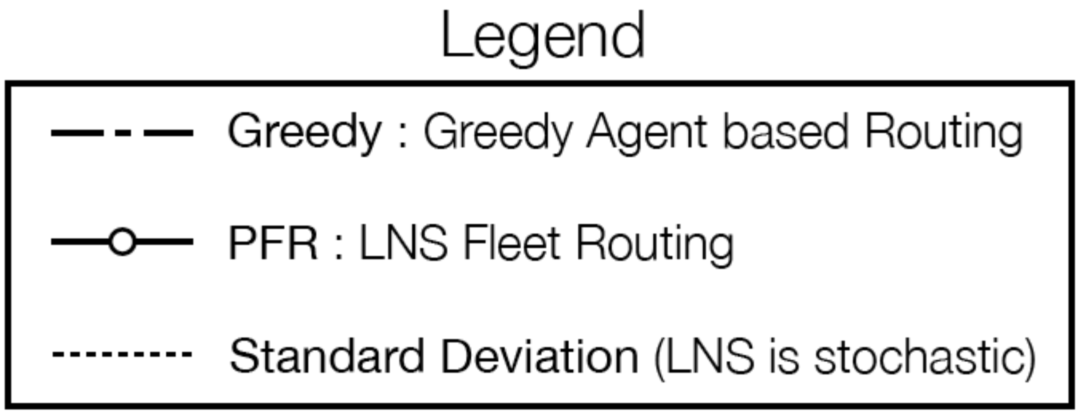
- Hurricane Scenarios from Los Alamos National Lab
  - Based on the United States Infrastructure
  - State of the art disaster scenario simulation tools (NHC)
- Instance sizes

Benchmark	n	m	a	Min Trip Lower Bound	Max Trip Lower Bound
BM1	25	4	3	6	27
BM2	25	5	3	60	84
BM3	25	5	3	0	109
BM4	30	5	3	35	109
BM5	100	20	3	82	223
BM6	25	5	18	0	140
BM7	30	10	18	7	23
BM9	250	10	18	7	23
BM10	500	20	18	13	45
BM12	1000	20	3	64	167

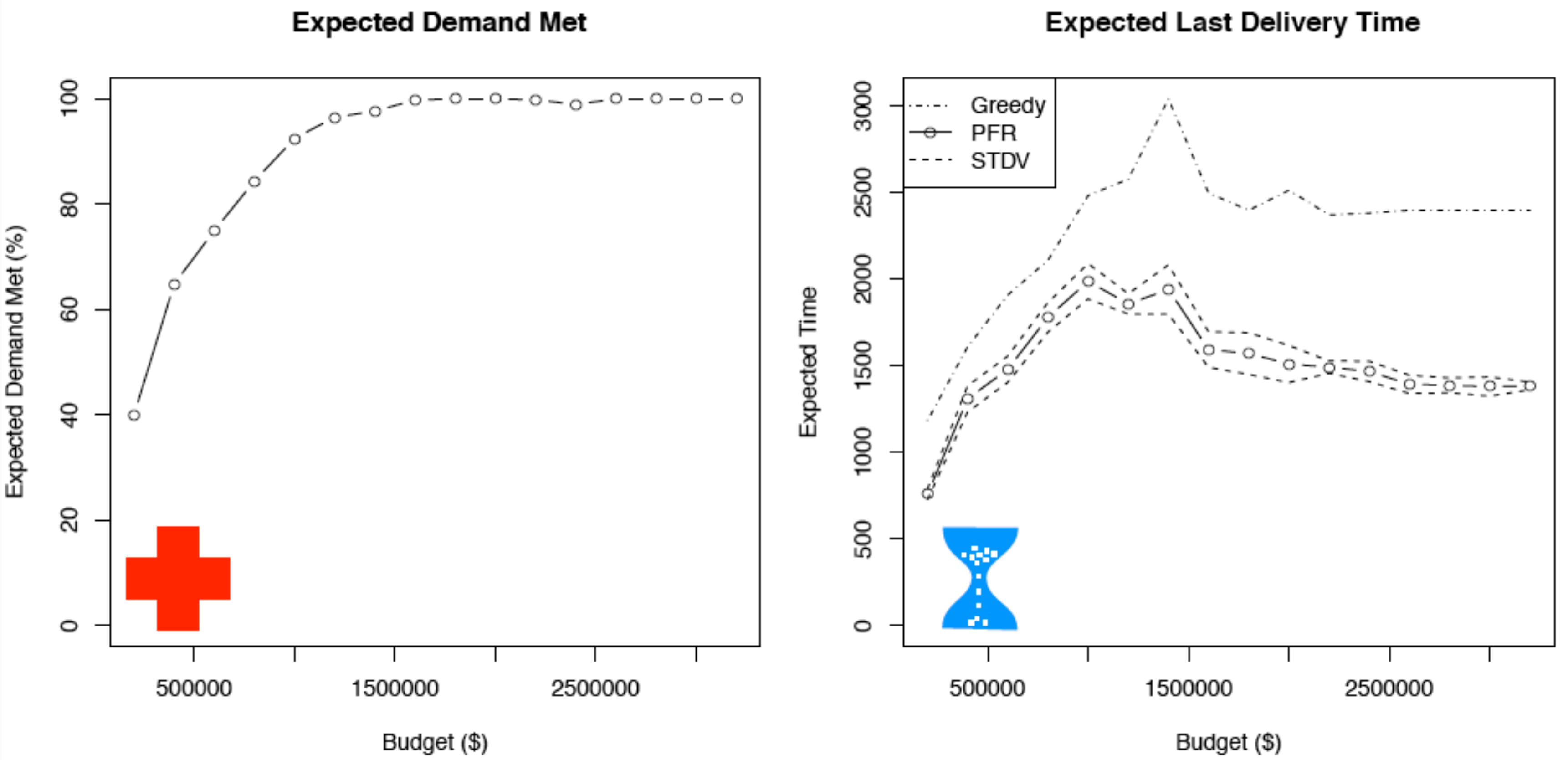
> 1,000,000 variables

Experimental Results: Water Supply

- Comparison with the practice in the field
  - Same storage model
  - Routing with a greedy-based agent routing
    - Every vehicle independently tries to deliver as much as possible



Experimental Results: Benchmark 5



Depots: 100 Vehicles: 20 Scenarios: 3 Trips: 220
Average Runtime: 1308 sec. - 520 sec.

Computational Difficulties

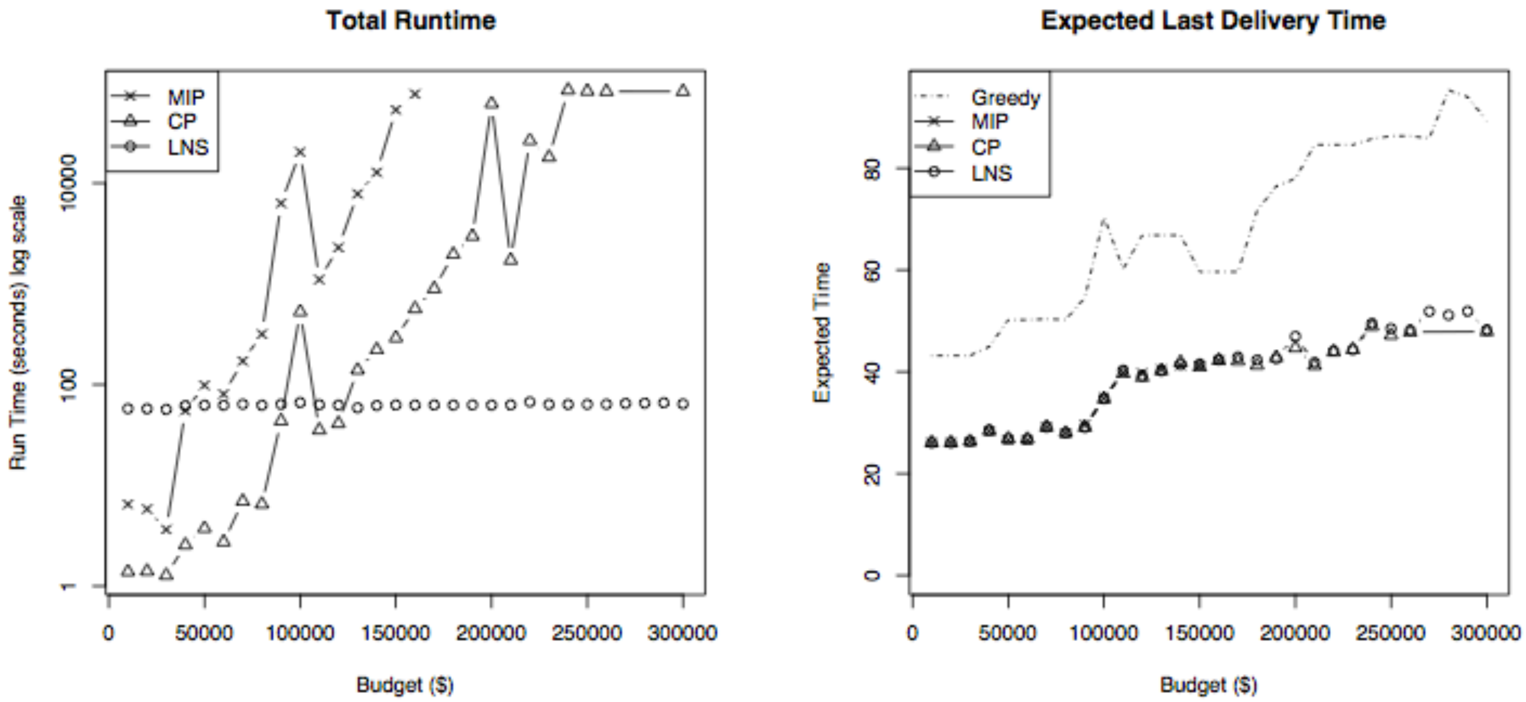
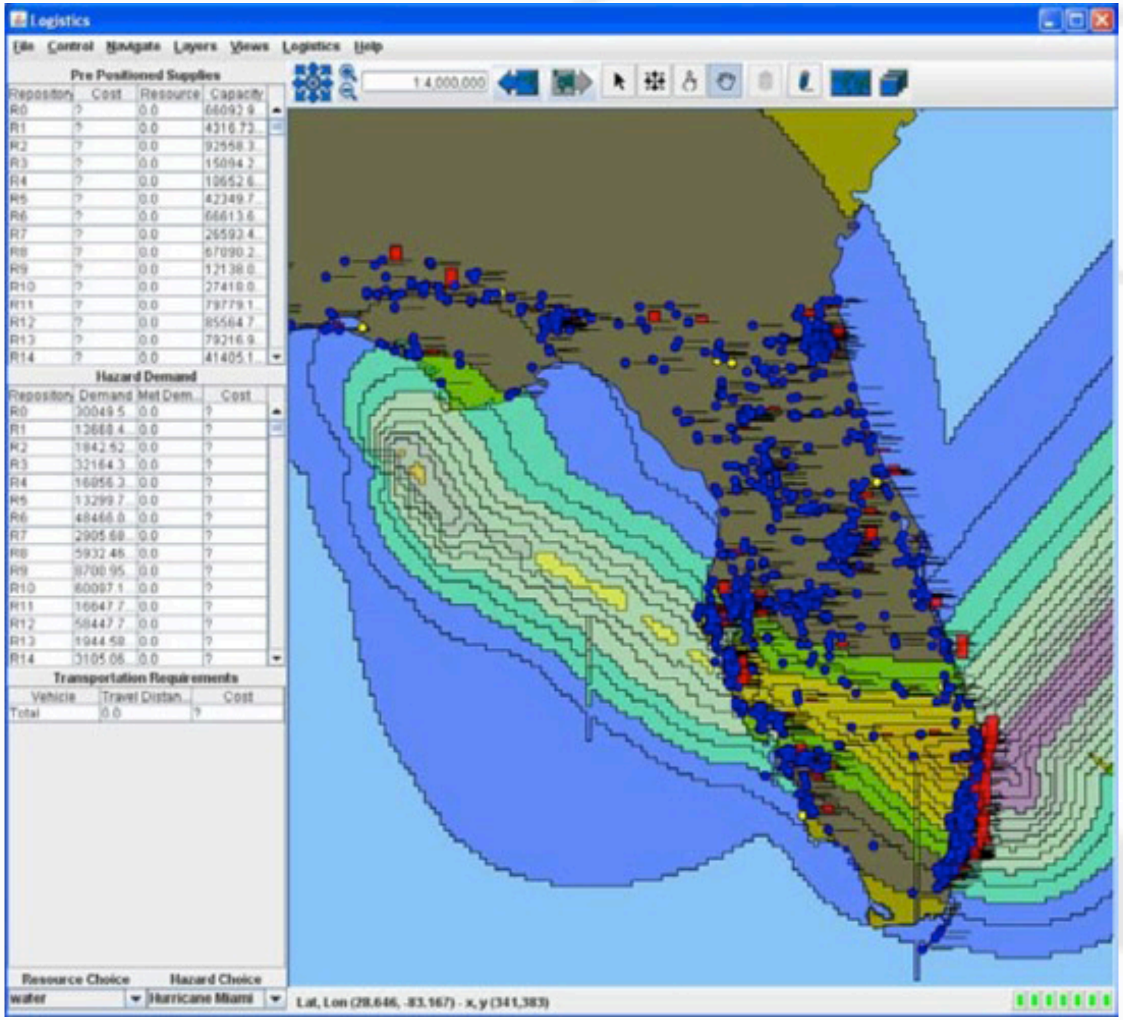


Figure 19: Quality and Runtime Comparison of LNS, CP, and MIP for the Fleet Routing Problem.

Disaster Preparedness and Recovery

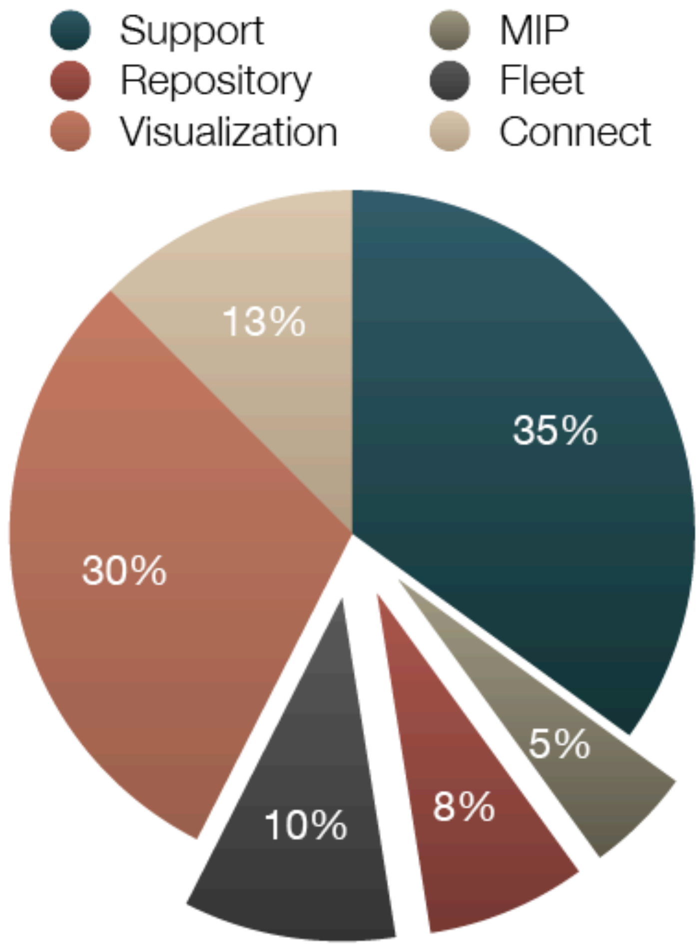


✓Deployed in LANL fast-response analysis and decision support tool.

✓Activated when a hurricane of category 3 or above threaten coastal areas

Comet Implementation: 1800 Lines

- 700 - Data-structures
- 100 - Storage MIP Model
- 150 - Repository Routing
- 200 - Fleet Routing
- 600 - Visualization
- 250 - Tie it all together
- All models 450 LOC



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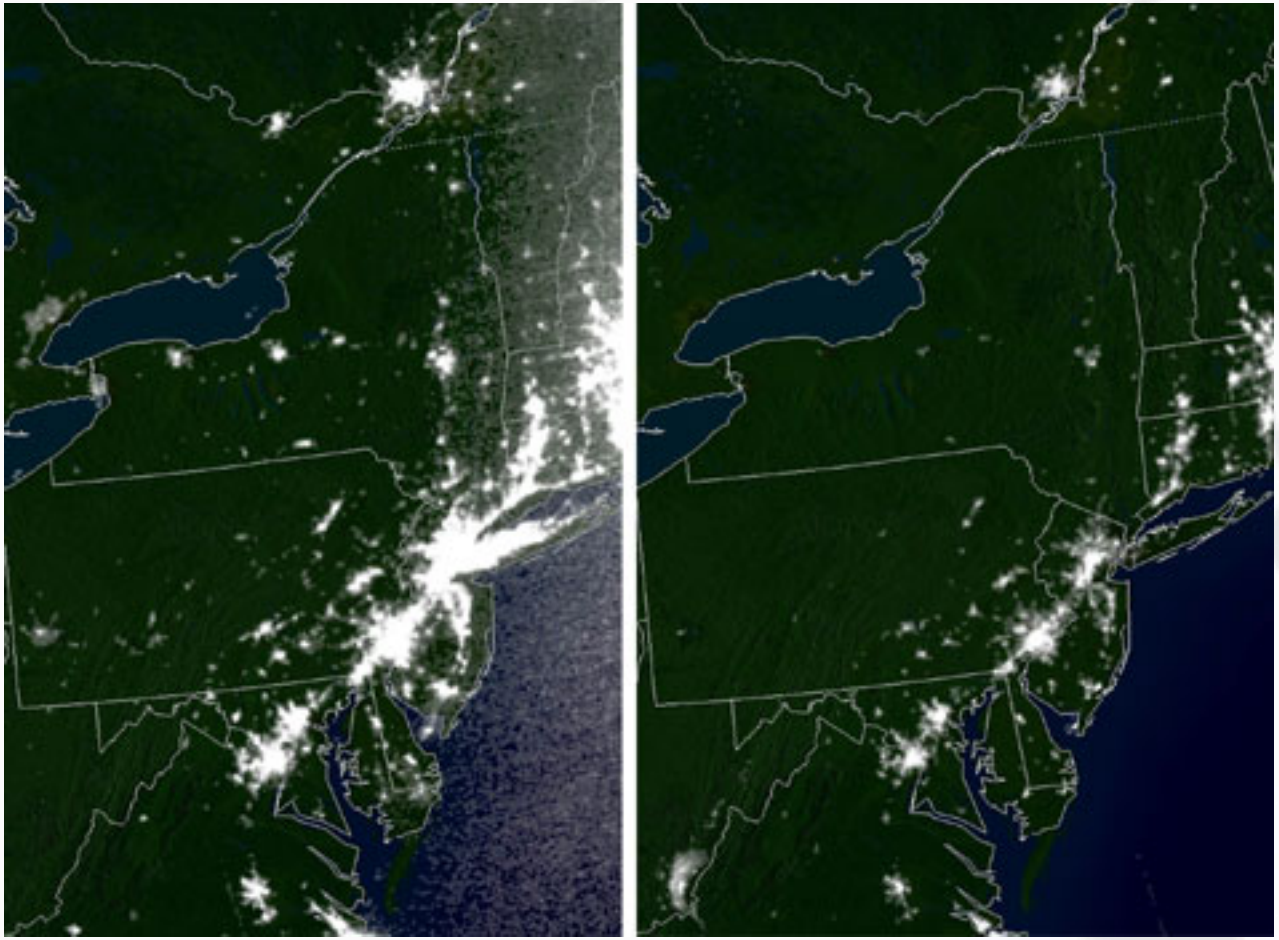
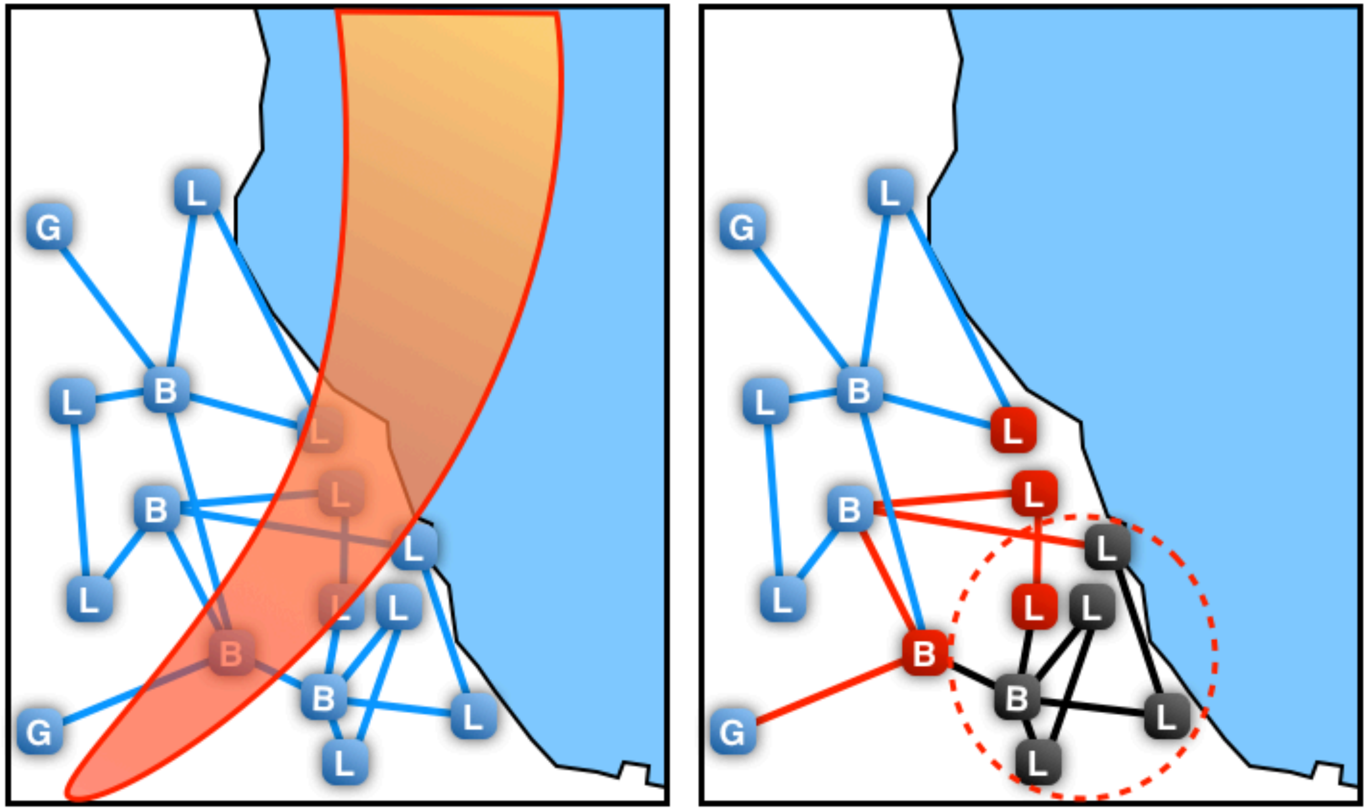
August 2003 Blackout



August 13, 9.03pm   August 13, 9.21pm

- ✓Grid overload
- ✓100 power plants shut down
- ✓50 millions people affected
- ✓ over 20 millions people in the dark for up to 24 hours

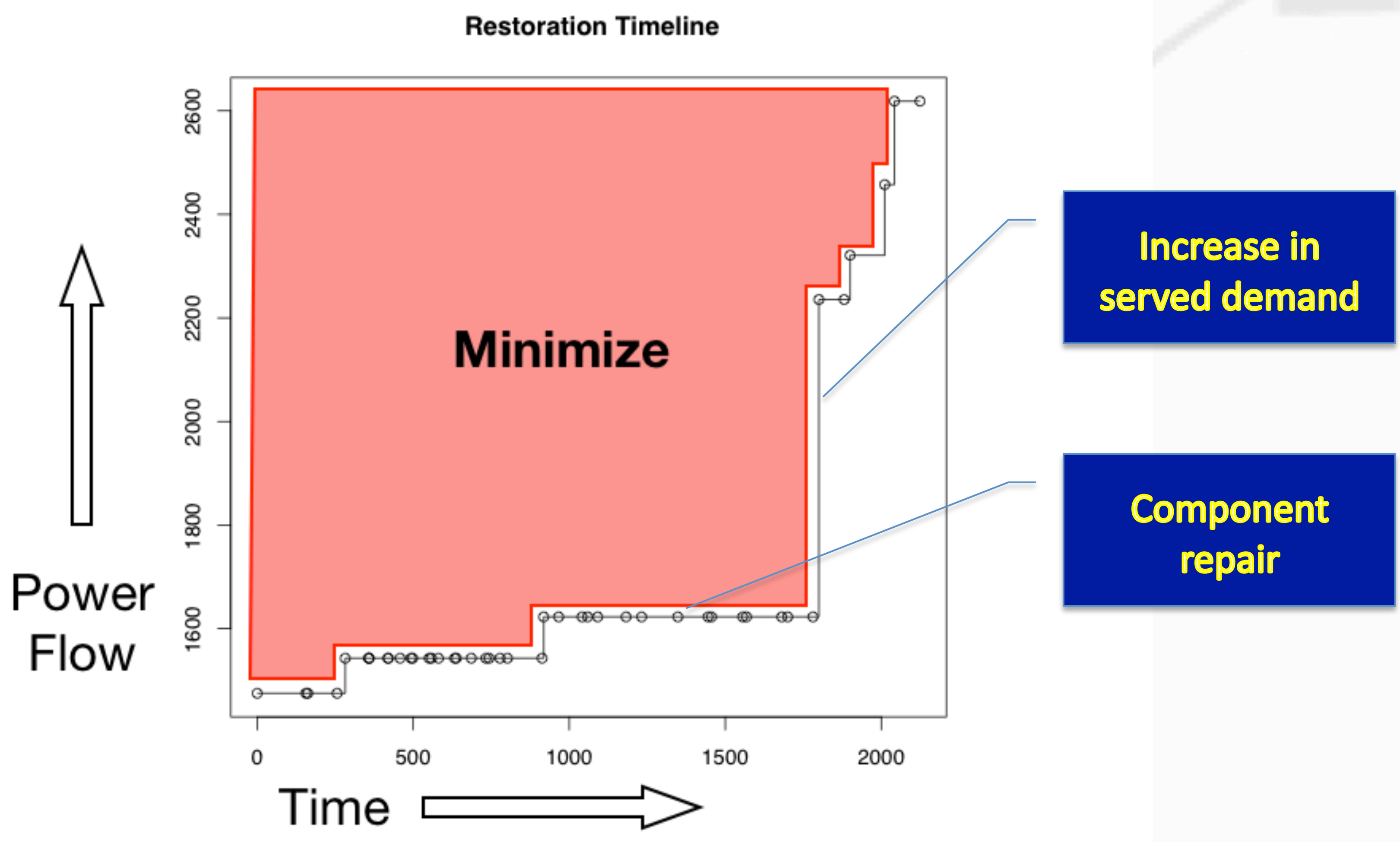
Disaster Effects on the Grid



Joint Repair and Power Restoration

- The challenge
  - Schedule a fleet of repair crews to repair the grid and minimize the overall size of the blackout after a disaster
- Two fundamental aspects
  - Scheduling the repairs (like in the SCDRP)
  - Scheduling the power restoration
  - Both are challenging in their own right
- Assumptions for Last-Mile Restoration
  - Steady state behavior of the power grid
  - Ability to shed load and generation continuously

Joint Repair and Power Restoration



Power Restoration

- Active Research for over 30 years
  - Steady state
  - Dynamic behavior and transient states
  - System configuration
- Main Assumption
  - Every component is working
  - The issue is in which order to activate them
- Traditional Approaches
  - Knowledge-based and expert systems: [Sagaguchi 83,Adibi 94]
  - Local Search: [Morelato 89, Mori 02]
  - MIP Optimization: [Delgadillo 10, Yolcu 83]
  - Hybridization of expert systems and optimization [Nagata 95,Huang 95]

Joint Repair and Power Restoration

Evaluating each (partial) solution is itself an optimization problem

Calculating Power Flow

- For each item, i, in the power network we need to solve the equations,

$$P_i = \sum_{k=1}^{n} |V_i||V_k|(g_{ik}\cos(\theta_i - \theta_k) + b_{ik}\sin(\theta_i - \theta_k))$$

$$Q_i = \sum_{k=1}^{n} |V_i||V_k|(g_{ik}\sin(\theta_i - \theta_k) + b_{ik}\cos(\theta_i - \theta_k))$$

Linearized DC Model

Conductance: small compared to susceptance

susceptance

close to θ_i - θ_k

Calculating Power Flow

- For each item, i, in the power network we need to solve the equations,

$$P_i = \sum_{k=1}^{n} |V_i||V_k|(g_{ik}\cos(\theta_i - \theta_k) + b_{ik}\sin(\theta_i - \theta_k))$$

$$Q_i = \sum_{k=1}^{n} |V_i||V_k|(g_{ik}\sin(\theta_i - \theta_k) + b_{ik}\cos(\theta_i - \theta_k))$$

real power

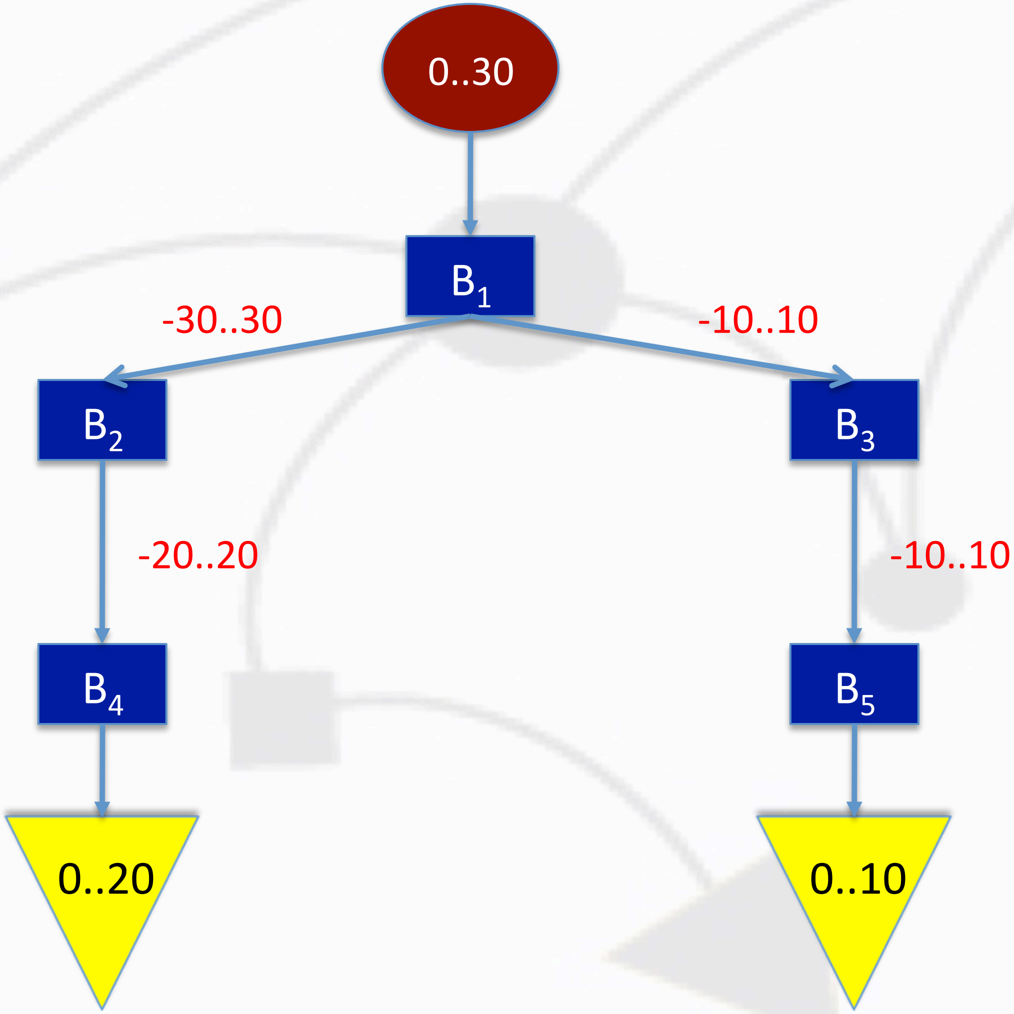
close to 1 in per unit system

reactive power: small compared to the real power

The Issue with AC Current

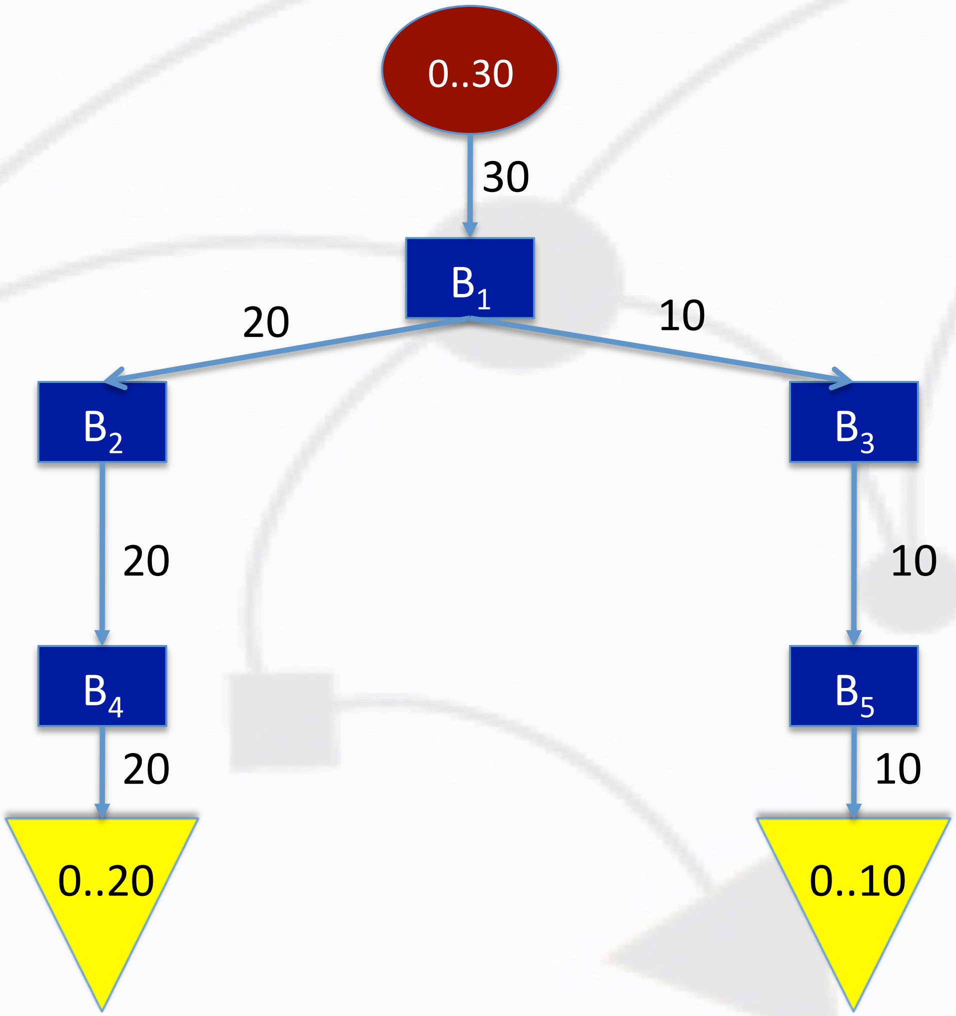
- Power Flow Optimization
  - Find how much to generate and the phase angles to maximize the served load
  - Large linear program (Linearized DC model)
- Power networks exhibit the Braess paradox
  - *"Cannot (fully) control the electricity flow"*
  - Activating new lines/buses/generators can decrease the overall served load
  - Bus angles

Braess Paradox

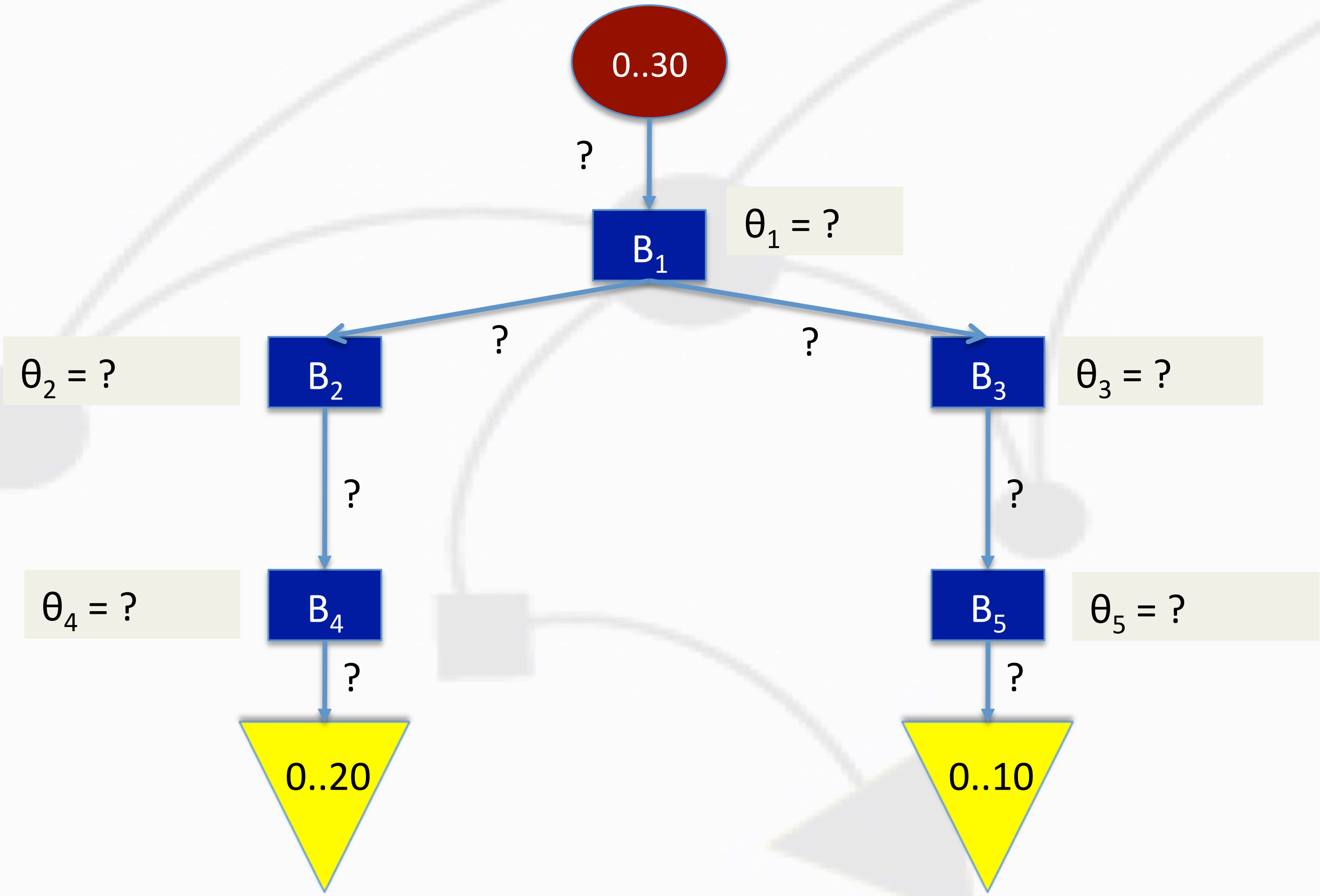


Adapted from [Bienstock 07]

Braess Paradox: Flow



Braess Paradox: Linearized DC Model



Braess Paradox: Linearized DC Model

$$\begin{aligned} &\textit{minimize} \quad P_4 + P_5 \\ &\textit{subject to} \end{aligned}$$

$$P_1 = P_{12} + P_{13}$$
$$P_{12} = P_{24}$$
$$P_{13} = P_{35}$$
$$P_{24} = P_4$$
$$P_{35} = P_5$$

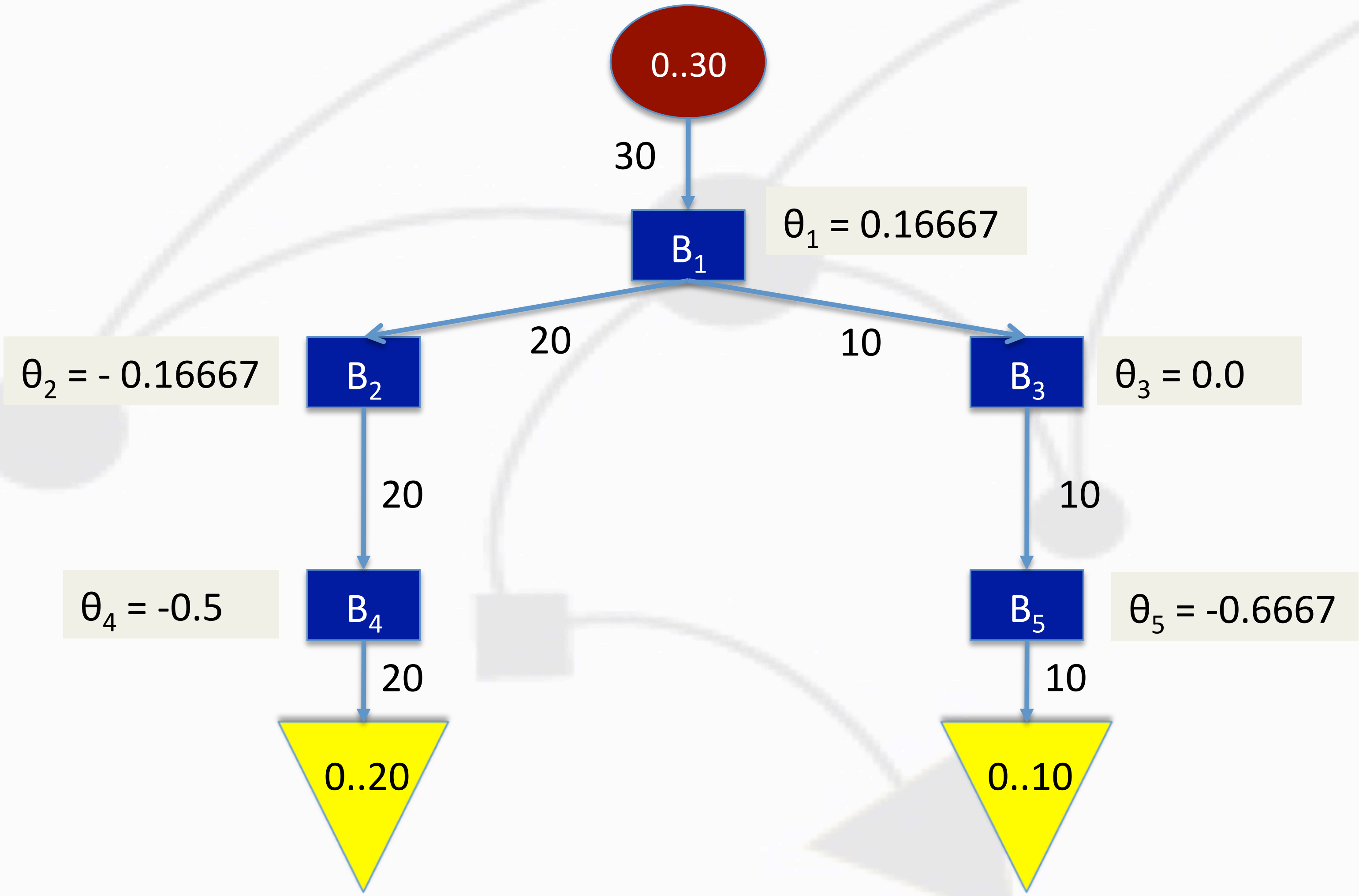
Kirchhoff's Law

$$P_{12} = b * (\theta_1 - \theta_2)$$
$$P_{13} = b * (\theta_1 - \theta_3)$$
$$P_{24} = b * (\theta_2 - \theta_4)$$
$$P_{35} = b * (\theta_3 - \theta_5)$$

Power definition

$$\theta_i \in -0.5..0.5 \quad (1 \leq i \leq 5)$$
$$P_1 \in 0..30, P_4 \in 0..20, P_5 \in 0..10$$
$$P_{12} \in -30..30, P_{13} \in -10..10$$
$$P_{14} \in -20..20, P_{35} \in -10..10$$

Braess Paradox: Linearized DC Model



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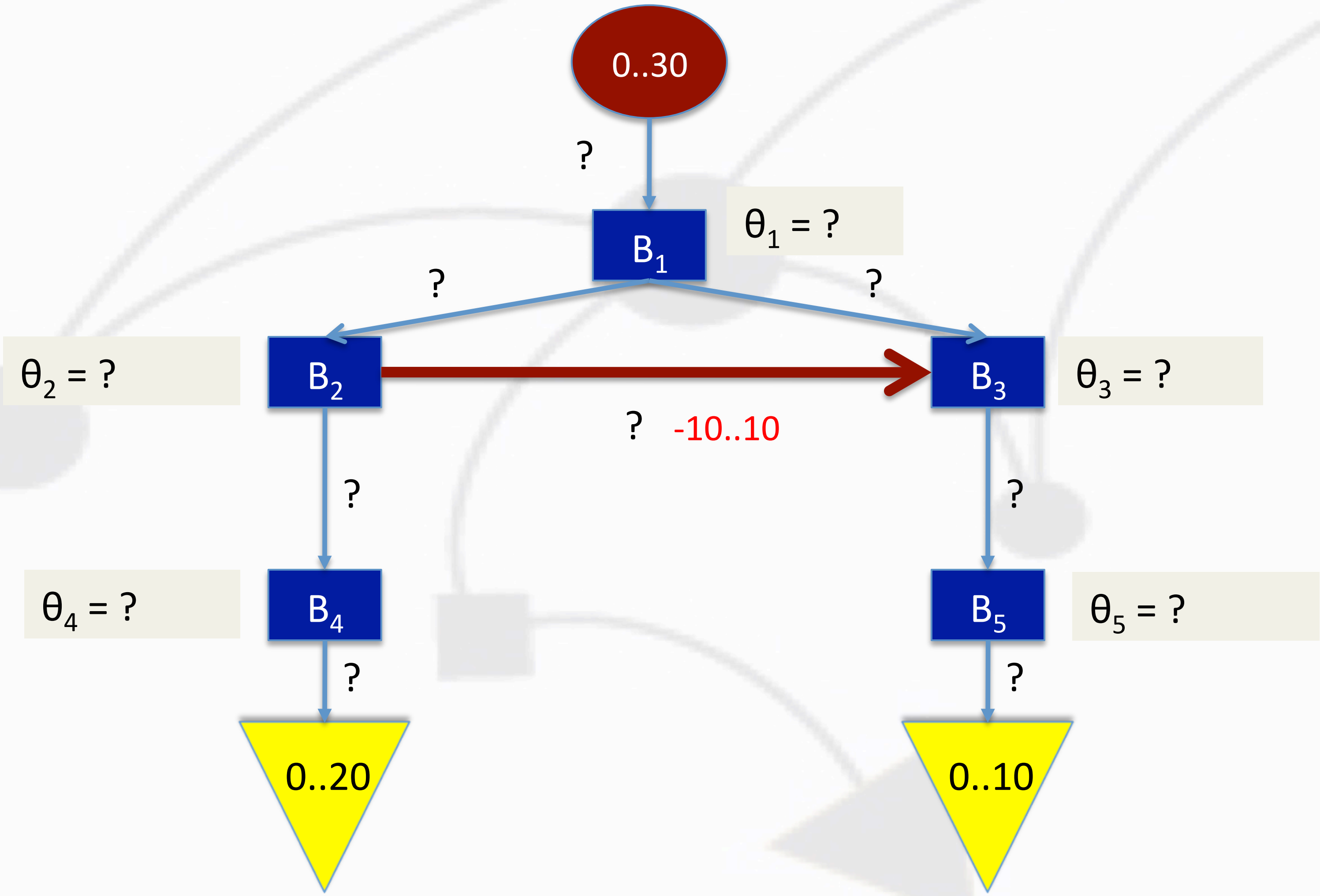
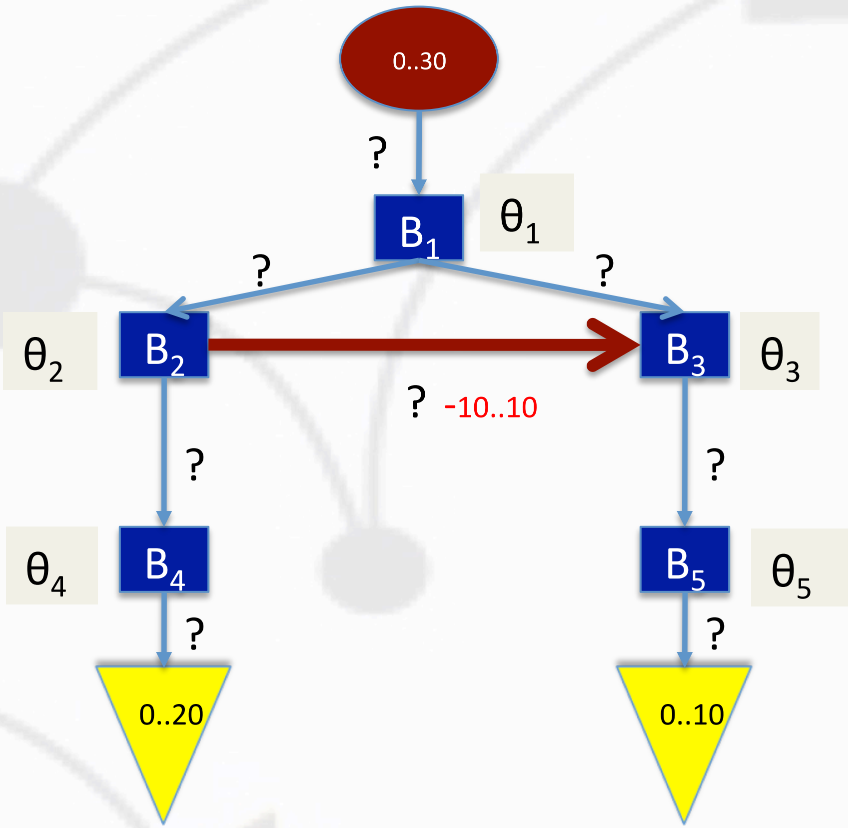
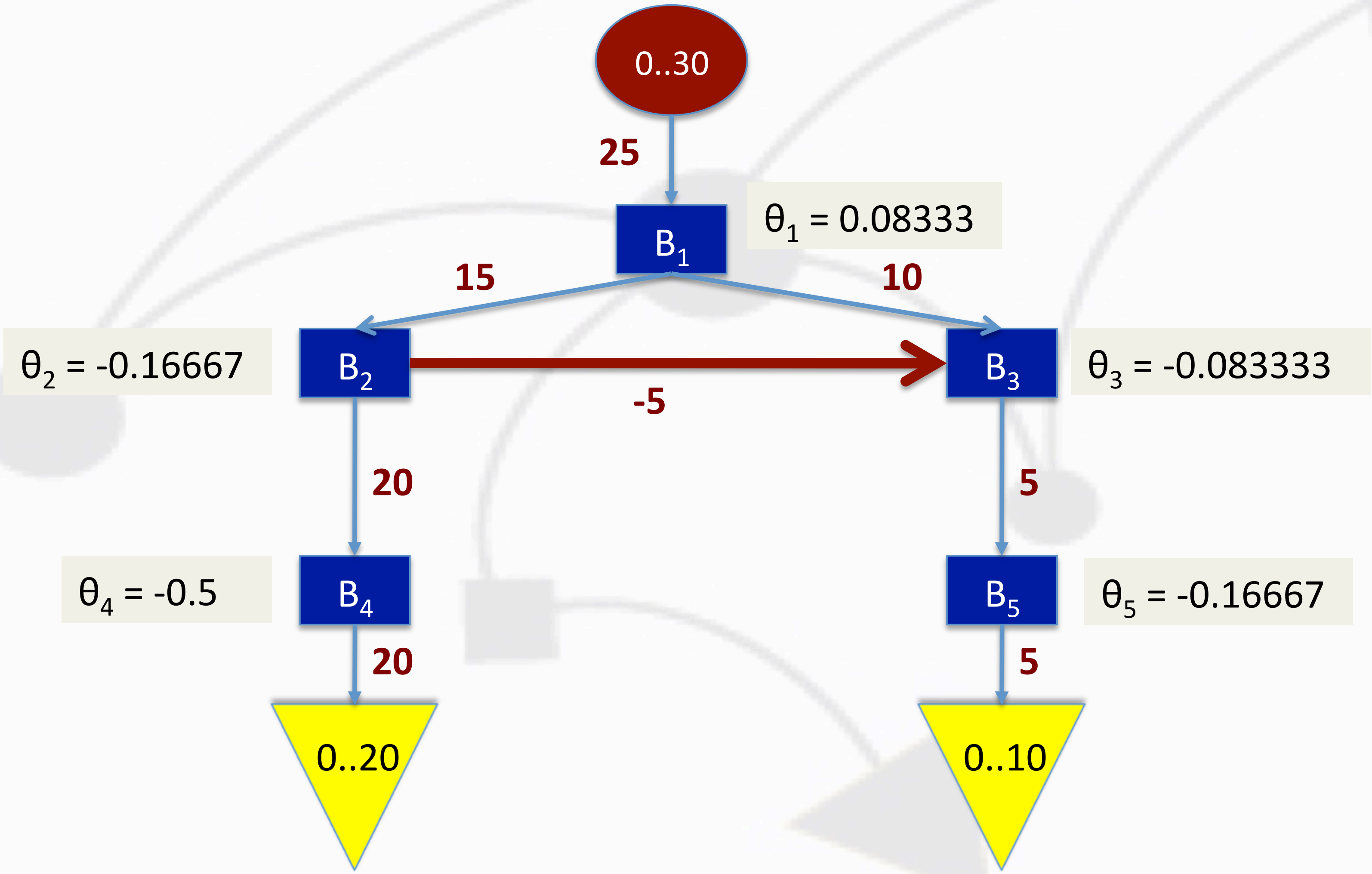


Braess Paradox: Linearized DC Model

$$
\begin{array}{ll}
\textit{minimize} & P_4 + P_5 \\
\textit{subject to} & \\
& P_1 = P_{12} + P_{13} \\
& P_{12} = P_{23} + P_{24} \\
& P_{13} + P_{23} = P_{35} \\
& P_{24} = P_4 \\
& P_{35} = P_5 \\
& P_{12} = b * (\theta_1 - \theta_2) \\
& P_{13} = b * (\theta_1 - \theta_3) \\
& P_{23} = b * (\theta_2 - \theta_3) \\
& P_{24} = b * (\theta_2 - \theta_4) \\
& P_{35} = b * (\theta_3 - \theta_5) \\
& \\
& \theta_i \in -0.5..0.5 \;\; (1 \le i \le 5) \\
& P_1 \in 0..30, P_4 \in 0..20, P_5 \in 0..10 \\
& P_{12} \in -30..30, P_{13} \in -10..10, P_{23} \in -10..10 \\
& P_{14} \in -20..20, P_{35} \in -10..10
\end{array}
$$



Braess Paradox: Linearized DC Model



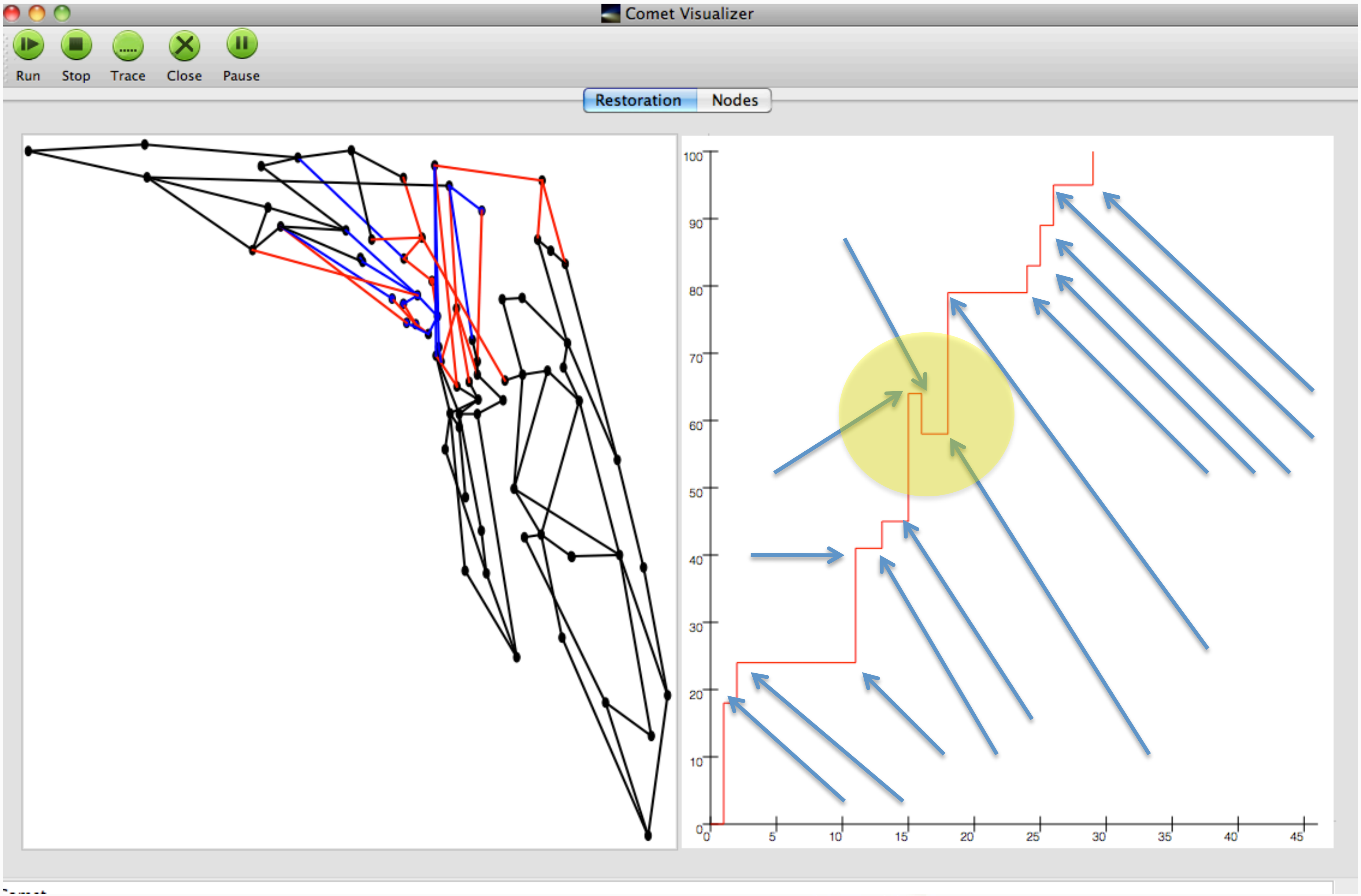
Consequence of Braess Paradox

- Evaluating a (partial) solution becomes an optimal activation problem
  - We need to decide which components to activate
- The power equation becomes

$$P_i^l = B_i \times z_i \times (\theta_{L_i^+} - \theta_{L_i^-})$$

- It is nonlinear: can be linearized since z_i is a 0/1 variable

$$0 \leq P_i^v \leq \hat{P}_i^v * z_i \quad \forall j \in N^b, \forall i \in N_j^g \cup N_j^l$$
$$-\hat{P}_i^l * z_i \leq P_i^l \leq \hat{P}_i^l * z_i \quad \forall i \in L$$
$$P_i^l \geq B_i * (\theta_{L_i^+} - \theta_{L_i^-}) + M * (\neg z_i) \quad \forall i \in L$$
$$P_i^l \leq B_i * (\theta_{L_i^+} - \theta_{L_i^-}) - M * (\neg z_i) \quad \forall i \in L$$



Comet Visualizer
Run
Stop
Trace
Close
Pause
Restoration
Nodes
100
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
45

Optimal Activation Problem

```
presolved problem has 1960 variables and 2186 constraints
   510 constraints of type <varbound>
  1475 constraints of type <linear>
   201 constraints of type <logicor>
Presolving Time: 0.52
time  | node   | dualbound     | primalbound  | gap
 1.0s |    1   | 1.602999e+02 |-0.000000e+00 | 100.00%
14.3s |    1   | 1.602999e+02 | 1.213604e+02 |  24.29%
 779s | 12012  | 1.602999e+02 | 1.228179e+02 |  23.38%
 812s | 12658  | 1.602999e+02 | 1.238971e+02 |  22.71%
 827s | 12858  | 1.602999e+02 | 1.263328e+02 |  21.19%
1019s| 18895  | 1.602999e+02 | 1.324728e+02 |  17.36%
1147s| 24867  | 1.602999e+02 | 1.353018e+02 |  15.59%
1276s| 33091  | 1.602999e+02 | 1.362924e+02 |  14.98%
1294s| 34851  | 1.602999e+02 | 1.419186e+02 |  11.47%
1958s| 91300  | 1.602999e+02 | 1.447137e+02 |   9.72%
5882s|435468 | 1.602999e+02 | 1.460944e+02 |   8.86%
 202m|  1038k | 1.602999e+02 | 1.464802e+02 |   8.62%
 253m|  1344k | 1.602999e+02 | 1.464802e+02 |   8.62%
```

Inputs:

$\mathcal{PN} = \langle N, L \rangle$	the power network
D	the set of damaged items
R	the set of repaired items

Variables:

$y_i \in \{0,1\}$	- item i is activated
$z_i \in \{0,1\}$	- item i is operational
$P_i^l \in (-\hat{P}_i^l, \hat{P}_i^l)$	- power flow on line i
$P_i^v \in (0, \hat{P}_i^v)$	- power flow on node i
$\theta_i \in (-\frac{\pi}{6}, \frac{\pi}{6})$	- phase angle on bus i

Maximize

$$\sum_{b \in N^b} \sum_{i \in N_b^l} P_i^v \tag{1}$$

Subject to:

$$y_i = 1 \quad \forall i \in N \setminus D \tag{2}$$

$$y_i = 0 \quad \forall i \in D \setminus R \tag{3}$$

$$z_i = y_i \quad \forall i \in N^b \tag{4}$$

$$z_i = y_i \wedge y_j \quad \forall j \in N^b, \forall i \in N_j^g \cup N_j^l \tag{5}$$

$$z_i = y_i \wedge y_{L_i^+} \wedge y_{L_i^-} \quad \forall i \in L \tag{6}$$

$$\sum_{j \in N_i^l} P_j^v = \sum_{j \in N_i^g} P_j^v + \sum_{j \in LI_i} P_j^l - \sum_{j \in LO_i} P_j^l \quad \forall i \in N^b \tag{7}$$

$$0 \le P_i^v \le \hat{P}_i^v * z_i \quad \forall i \in N_j^g \cup N_j^l \tag{8}$$

$$-\hat{P}_i^l * z_i \le P_i^l \le \hat{P}_i^l * z_i \quad \forall i \in L \tag{9}$$

$$P_i^l \ge B_i * (\theta_{L_i^+} - \theta_{L_i^-}) + M * (\neg z_i) \quad \forall i \in L \tag{10}$$

$$P_i^l \le B_i * (\theta_{L_i^+} - \theta_{L_i^-}) - M * (\neg z_i) \quad \forall i \in L \tag{11}$$

Figure 1: A MIP Model for the Unserved Load.

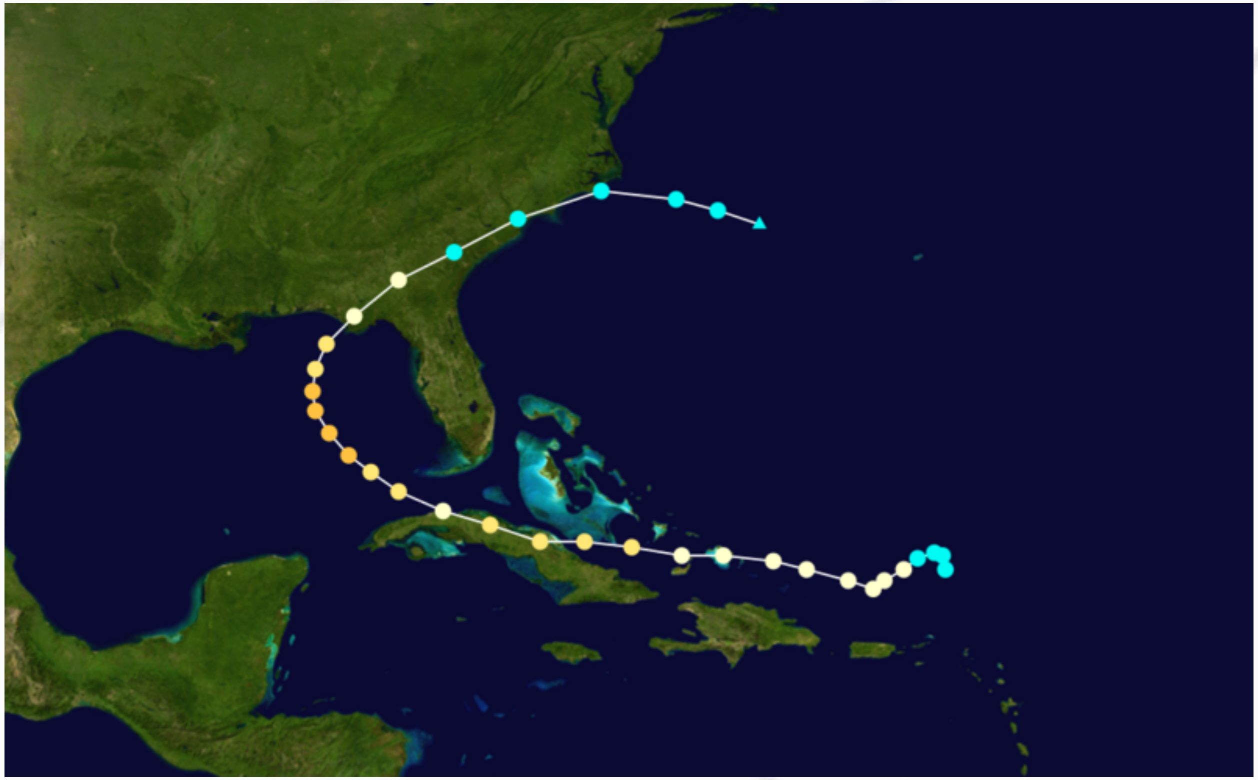
Constraint Injection

- Key motivation: decouple power restoration and routing
  - But routing must give a high-quality restoration
- Inject restoration constraints into the routing
  - Precedence constraints on the repairs
  - Pickup and delivery routing with precedence constraints and minimization of the sum of repair times
- Which constraints to inject?
  - Solve two power restoration problems
  - Give a "good" set of precedence constraints
  - Relax some of them after routing for post-processing

Constraint Injection

- 4-step approach
  - Minimum Set Restoration Problem
    - Find a small set of components to restore the power flow: MIP (small instances) or LNS over MIP
  - Restoration Ordering Problem
    - Choose the restoration order: LNS over MIP
  - Pick and Delivery Routing with Precedences
    - Schedule the repairs: LNS over CP
  - Relaxing inter-vehicles injected constraints

Demo Kate (?)



- Flooding and power outages across 90% of Tallahassee

Experimental Results: Benchmarks

- National Hurricane Center Simulation Tools
- Infrastructure of the United States
  - Power and Transportation Networks
- Significantly larger than other work on related problems
- Comparison with practice in the field

Benchmark	$\|V\|$	$\|S\|$	$\|N \cup L\|$	$\max(\|J\|)$
BM1	13	3	326	22
BM2	13	18	233	100
BM3	13	18	266	61
BM4	13	18	326	121

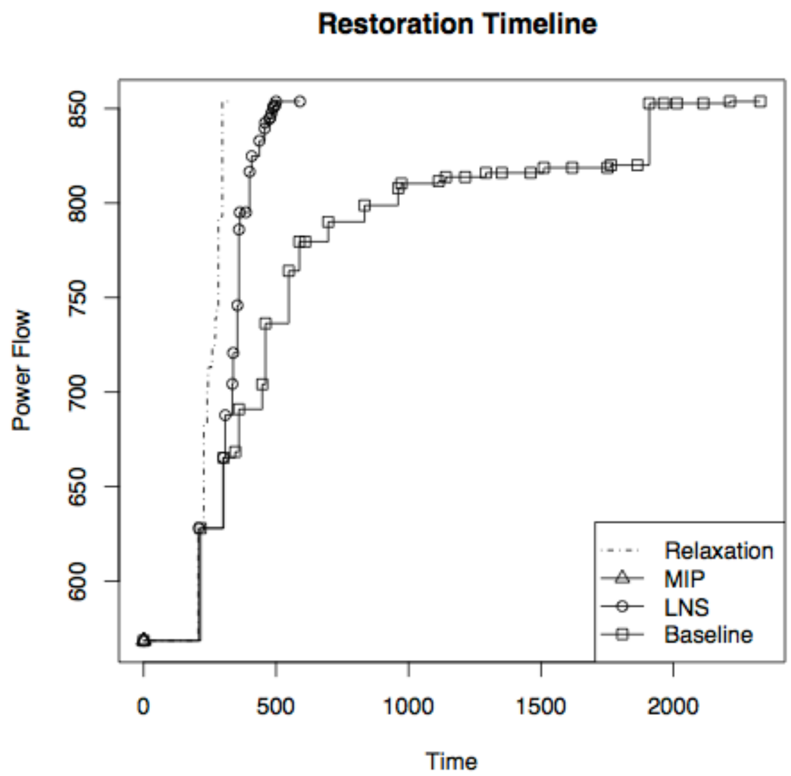
Repair crews

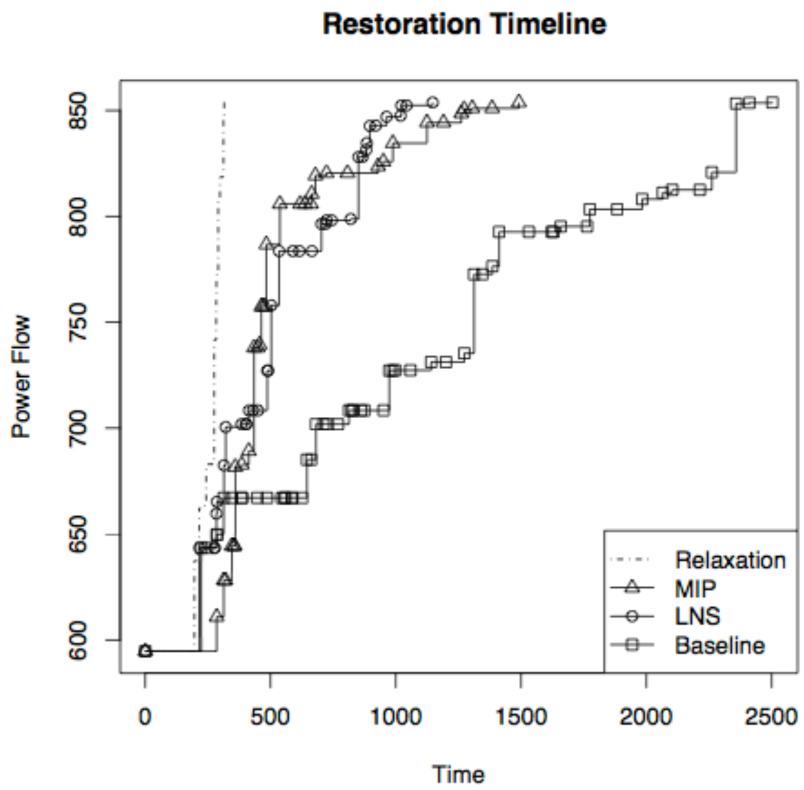
Scenarios

grid size

Damage size

Experimental Results: Quality





41 damaged items

67 damaged items

50 minutes of CPU time

Outline

- Motivation
- Disaster preparedness & recovery for a single commodity
  - *CPAIOR-10, CPAIOR-11*
- Last mile recovery of electrical power systems
  - *17th Power Systems Computation Conference (PSCC'11)*
- *Strategic stockpiling of power supplies for disaster recovery*
  - *2011 IEEE Power & Energy Annual Conference (PES'11)*
- Conclusion and Future Work

(Joint work with C. Carleton and R. Bent)

Strategic Stockpiling of Power Supplies

- Decide which supplies to stockpile before a disaster
  - Inputs are scenarios
  - Outputs is how many generators, buses, lines, … to stockpile
  - Objective is to maximize the expected/robust load
- Prepare for all the hurricanes that can hit Florida in 2011
  - Scenarios correspond to different hurricane paths: Miami, Eastern Florida, North Florida, ….
- Two approaches
  - An exact MIP Model
  - A constraint-based column-generation model

Constraint-Based Column Generation

- A configuration specifies a “global” stockpiling decision
  - How many components of each type: $(w_1,\ldots,w_k)$
- Master Problem
  - Given existing configurations for the scenarios, choose configurations that maximize the expected/robust served load
- Subproblem for each scenario
  - Generate a configuration and its associated served load
  - On demand
    - Too many configurations to enumerate them all
  - *Generating a configuration is an activation problem!*

Configurations

Scenario 3				
Gen	Bus	Line	Tran	Flow
1	0	0	0	1243
0	1	0	0	1200
0	0	1	0	700
0	0	0	1	200
1	1	0	0	2042
1	0	1	0	1821
1	0	0	1	1545

Master Problem

Let:

$\mathcal{W}$ - the set of configurations
w_t - the amount of components of type t in $w \in W$
$flow_{ws}$ - the served power for w in scenario s

Variables:

$x_t \in \mathcal{N}$ - number of stockpiled items of type t
$y_{ws} \in \{0,1\}$ - 1 if configuration w is used in s
$flow_s \in \mathcal{R}^+$ - power flow for scenario s

Maximize:

$$\sum_{s \in S} p_s * flow_s \quad (1)$$

Subject To:

$$\sum_{t \in T} v_t * x_t \leq \sum_l c_l \quad (2)$$

$$\sum_{w \in W} w_t * y_{ws} \leq x_t \ \forall s, t \quad (3)$$

$$\sum_{w \in W} y_{ws} = 1 \ \forall s \quad (4)$$

$$\sum_{w \in W} flow_{ws} * y_{ws} = flow_s \ \forall s \quad (5)$$

Decision variables

Which configuration for scenario s

Expected served load

Storage capacities

Deriving the stockpiling decisions

One configuration per scenario

Flow of the configuration

Master Problem

Let:

$\mathcal{W}$ - the set of configurations
w_t - the amount of components of type t in $w \in W$
$flow_{ws}$ - the served power for w in scenario s

Variables:

$x_t \in \mathcal{N}$ - number of stockpiled items of type t
$y_{ws} \in \{0, 1\}$ - 1 if configuration w is used in s
$flow_s \in \mathcal{R}^+$ - power flow for scenario s

Maximize:

$$\sum_{s \in S} p_s * flow_s \quad (1)$$

Subject To:

$$\sum_{t \in T} v_t * x_t \leq \sum_{l} c_l \quad (2)$$

$$\sum_{w \in W} w_t * y_{ws} \leq x_t \ \forall s, t \quad (3)$$

$$\sum_{w \in W} y_{ws} = 1 \ \forall s \quad (4)$$

$$\sum_{w \in W} flow_{ws} * y_{ws} = flow_s \ \forall s \quad (5)$$

- ✓ No mention of the power grid; The relevant information is encapsulated inside the configurations
- ✓ Derivation of the stockpiling decisions from the decisions of every scenarios.

Constraint-Based Column Generation

- Generate “interesting” configurations
  - for each scenario independently
- How to generate a configuration?
  - Optimal activation problem under storage constraints
  - Hard computationally
- What is an interesting configuration?
  - High-quality for the scenario (maximize served load)
  - Inject information from other scenarios (storage)
    - To reach good overall quality

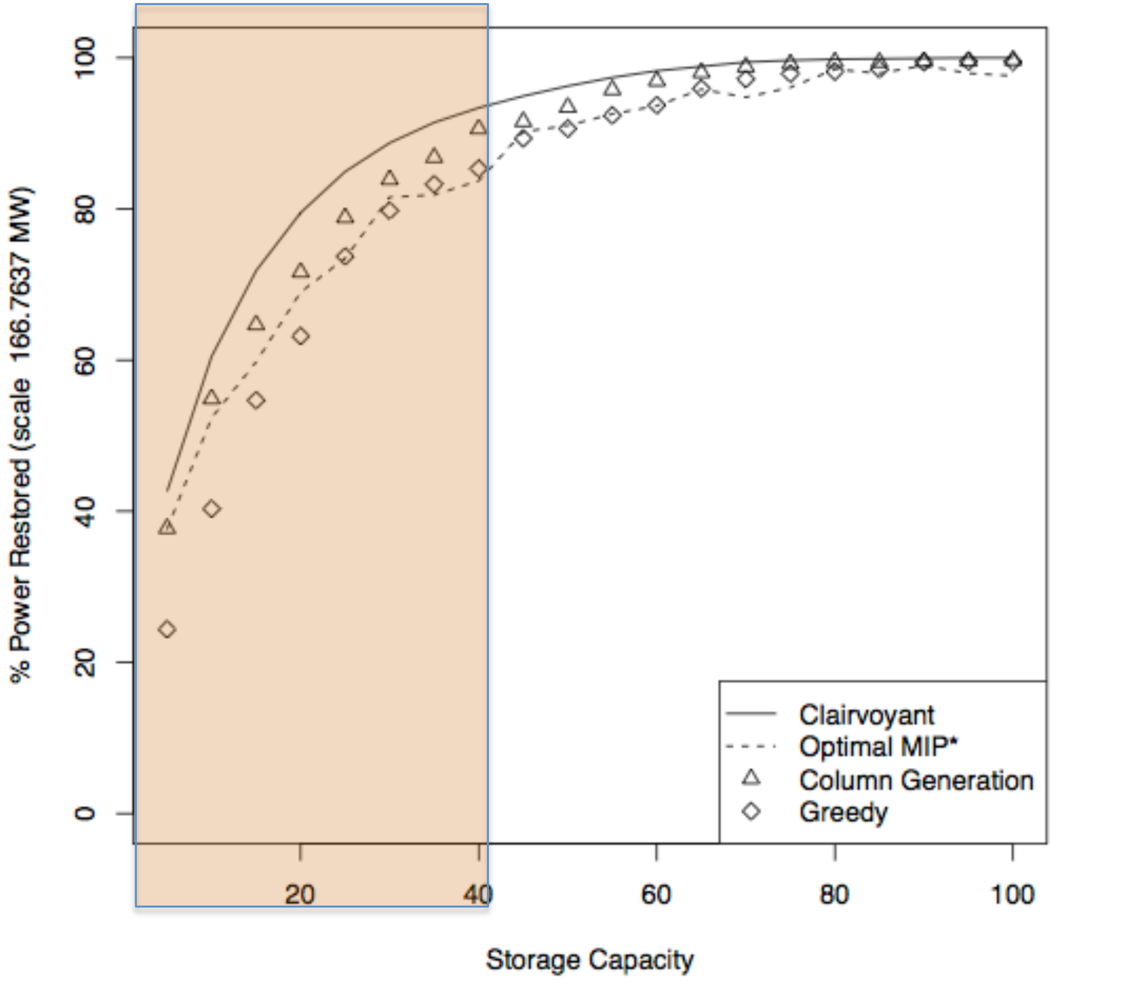
Constraint-Based Column Generation

- Two types of configurations: selfless and selfish
- "selfless" configuration for scenario s
  - Solve the master for all other scenarios to obtain w
  - Find the best configuration for s given the decisions w
- "selfish" configuration for scenario s
  - Scenario s would like configuration w in the master but cannot.
  - Generate the best configuration for other scenarios given w

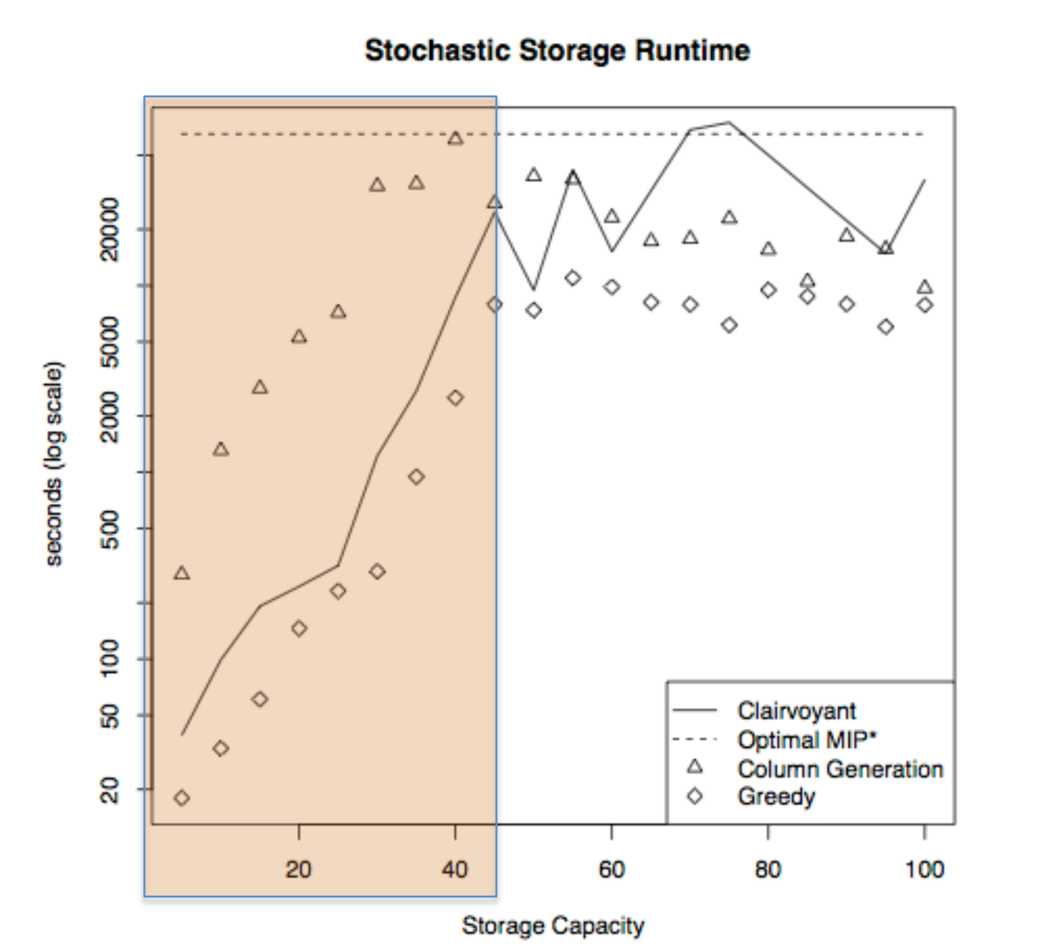
Experimental Results: Quality

Benchmark	$\|N\|$	$\|S\|$	$\max_{s \in S}(\|D_s\|)$
BM1	326	3	22
BM3	266	18	61
BM4	326	18	121
BM5	1789	4	255

TABLE I
FEATURES OF THE PSSSP BENCHMARKS.



Experimental Results: Runtime



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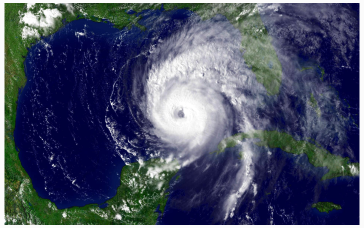
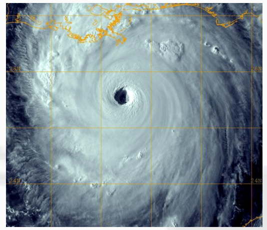


Conclusion

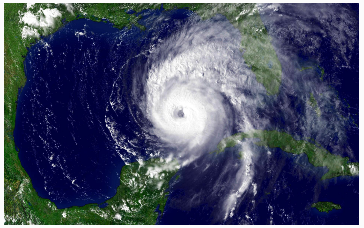


- Last-Mile Disaster Preparedness and Recovery
  - Single commodity and power grid
  - Significant progress over practice in the field
  - High-quality solutions with the time constraints
- Optimization technology
  - Mixed integer programming
  - Constraint programming
  - Large neighborhood search
  - Constraint-based column generation
  - Constraint injection

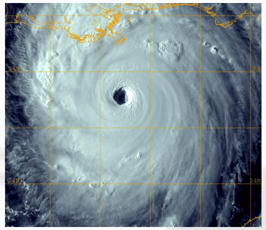
Numerical aspects

Combinatorial aspects

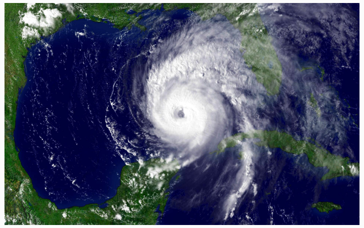
Decoupling



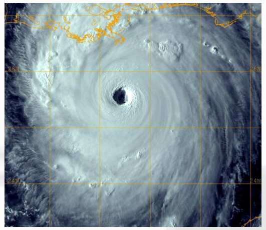
Multiple Infrastructures



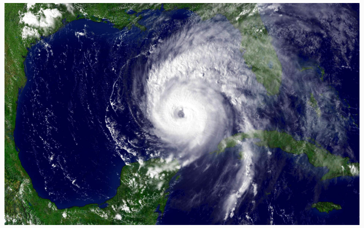
- Generalize to Interdependent infrastructures
  - e.g., transportation, gas, water and power grid infrastructures
- Dependencies between the infrastructures
  - Repair the roads before getting to the grid
  - Need power to activate gas generators (and vice versa)
- Different agents for the infrastructures
  - Common goal but also individual objectives
  - Beautiful results in computational game theory [Larson 2011]



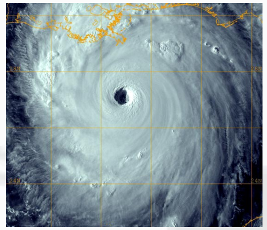
Joint Assessment and Repair



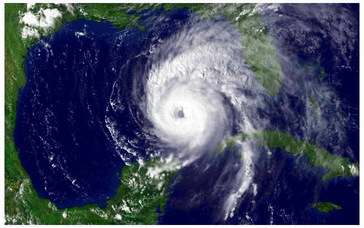
- Joint damage assessment and repair
  - Need to discover the damages in order to plan effectively
    - Uncertainty is exogenous but need actions to reveal it
- Basic approach: AMSAA
  - Formulate as a MDP
  - Use a good, domain-specific evaluation function
    - 2-stage stochastic optimization after relaxing the anticipatory constraints
  - Use "find and revise" algorithms guided by upper bounds
    - Lower bounds are easy to get since we have scenarios
- Main open issue is scalability



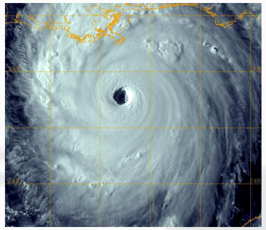
International Relief Effort



- Large-Scale International Relief Effort
  - Large one-time supply chain [Ergun et al., 2010]
    - prepositioning, response, recovery
  - Scheduling ~ 100,000 activities
- Multi-modal resources
  - Planes, ships, trucks, …
- Multiple organizations
  - Red Cross, Walmart, UN, Government, …



More globally



- Integration of Planning and Response
  - Planning and response are somewhat artificially separated
  - In practice, they need to be interleaved
- “Online” stochastic planning and scheduling
  - Planning and response actions, and the disaster, change the state of the networks, resources, … over time
- Tremendous opportunity for the ICAPS community.