Strategic Planning for Power System Restoration

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NISAC
RestoreSims

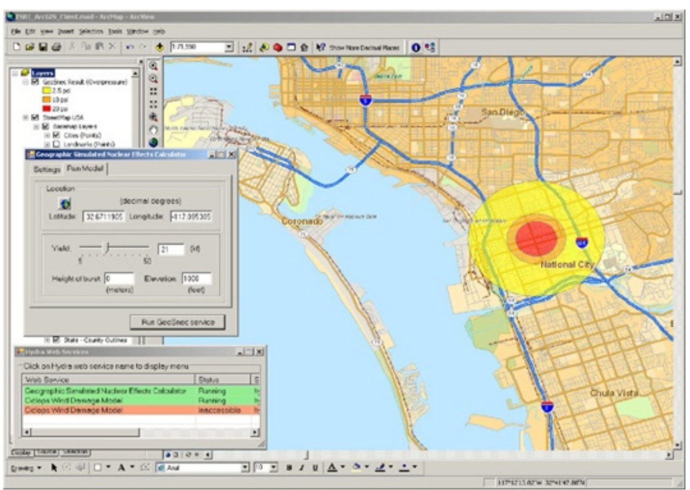
LA-UR 11-06362

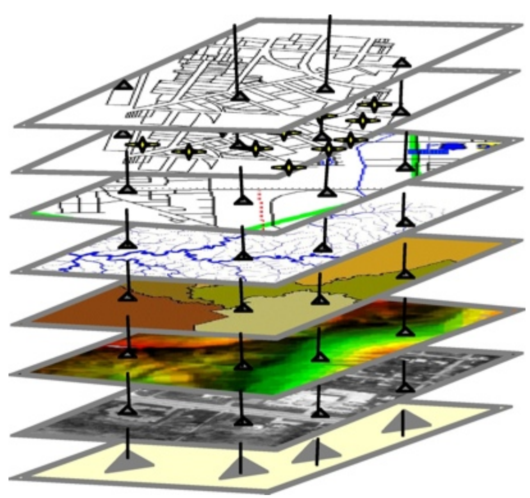

How should the U.S. prepare for the next
Category-5 Hurricane?

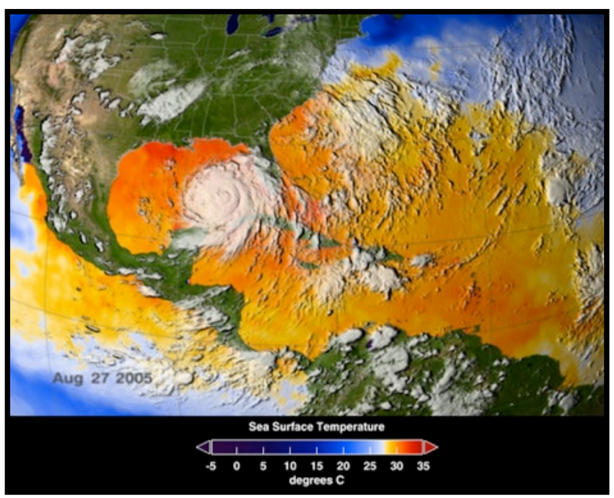
National Infrastructure Simulation and Analysis Center (NISAC)

- Founded by the Department of Homeland Security (DHS) to,

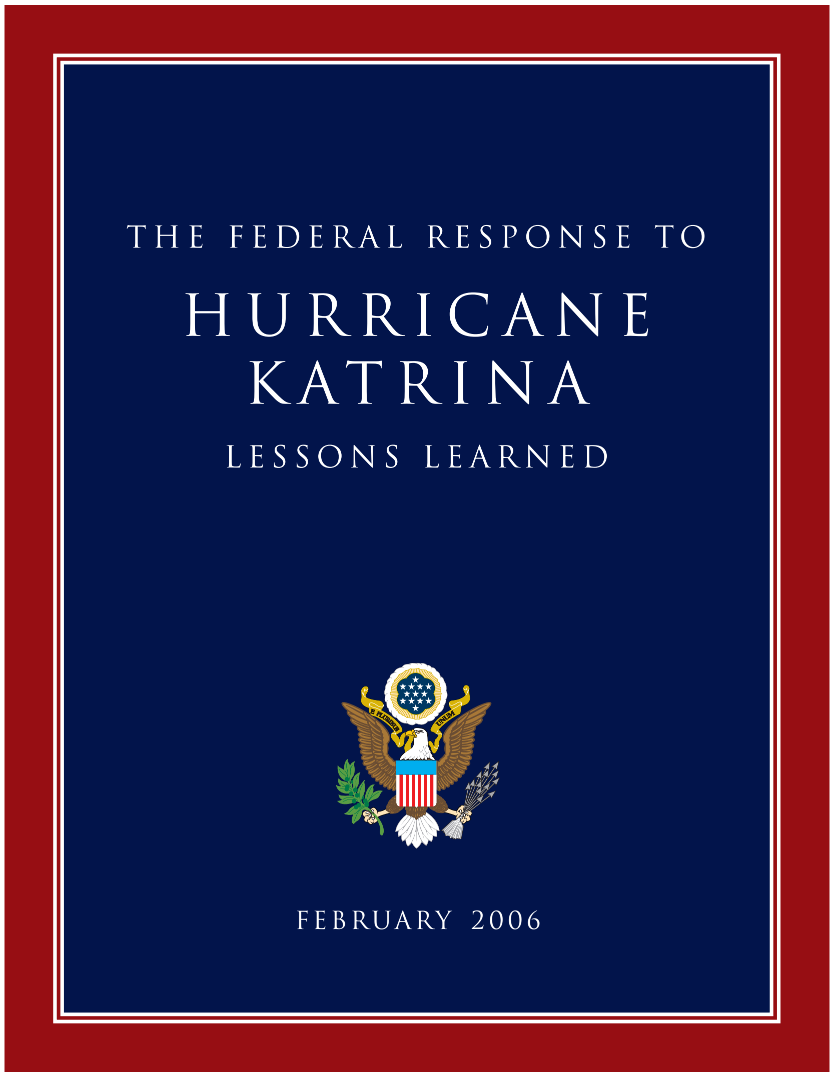
"...address critical infrastructure protection issues related to counterterrorism, threat assessment, and risk mitigation."







National Infrastructure Simulation and Analysis Center (NISAC)



- *Pre-Katrina:* NISCA focused on providing situational awareness. (i.e. What is going to happen?)

- *Post-Katrina:* The need for decision support is recognized. (i.e. How can we mitigate negative effects and use resources more effectively?)

- DHS asked NISAC to provide **“fast-response”** analysis and decision support when major disasters have occurred or are pending.

This Contribution to NISAC's *Fast-Response*

How to stockpile power system components throughout a state to minimize the restoration time after a natural disaster.

This Contribution to NISAC's ***Fast***-*Response*

*How to **stockpile power system** components throughout a state to minimize the **restoration time** after a **natural disaster**.*

1) Capacitated **warehouse location**

2) Vehicle **routing** of repair crews

3) **Non-linear** system modeling

4) Disasters are **stochastic**...
damage may vary significantly

5) Solve as **fast** as possible (minutes/hours, not days)

Consequences of the ***Fast***-*Response* Context

*Context: How to **stockpile power system** components throughout a state to minimize the **restoration time** after a **natural disaster**.*

- Due to the problem complexity and runtime constraints, proving solution optimality is out of reach.
- Stochasticity of disasters means a globally optimal solution is less critical.
- Our Goals:
    - Improve over current “best practices”
    - Bound the solution quality using relaxations

Overview

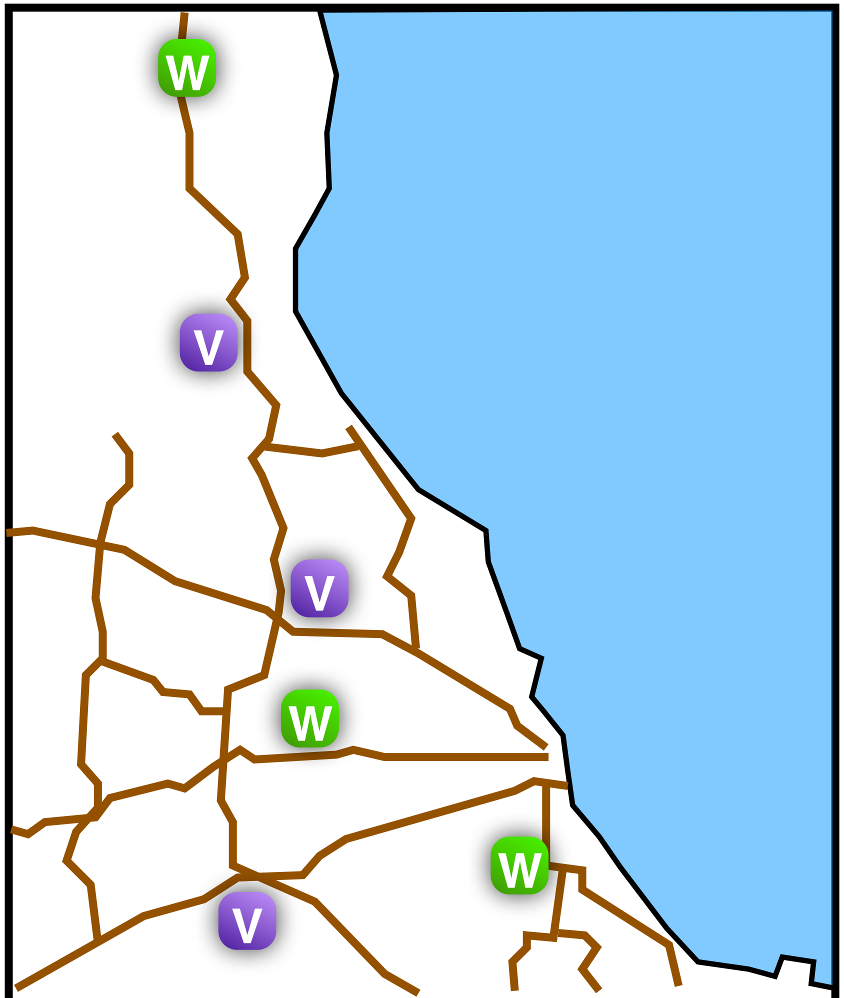
- Motivation
- Problem Formulation
    - Modeling Infrastructure Networks
- Basic Approach
    - Stochastic Storage Problem
    - Restoration Routing Problem
    - Combined Results
- Future Work

Problem Formulation

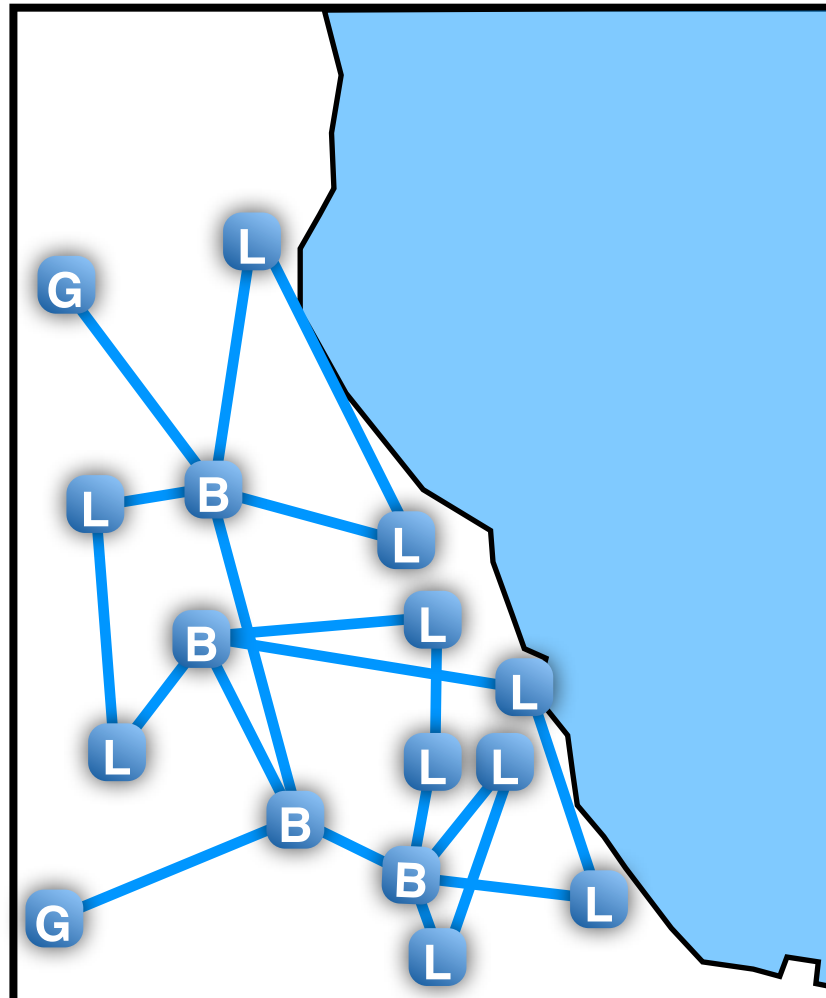
What do we know?

What do we know?

Infrastructure Systems



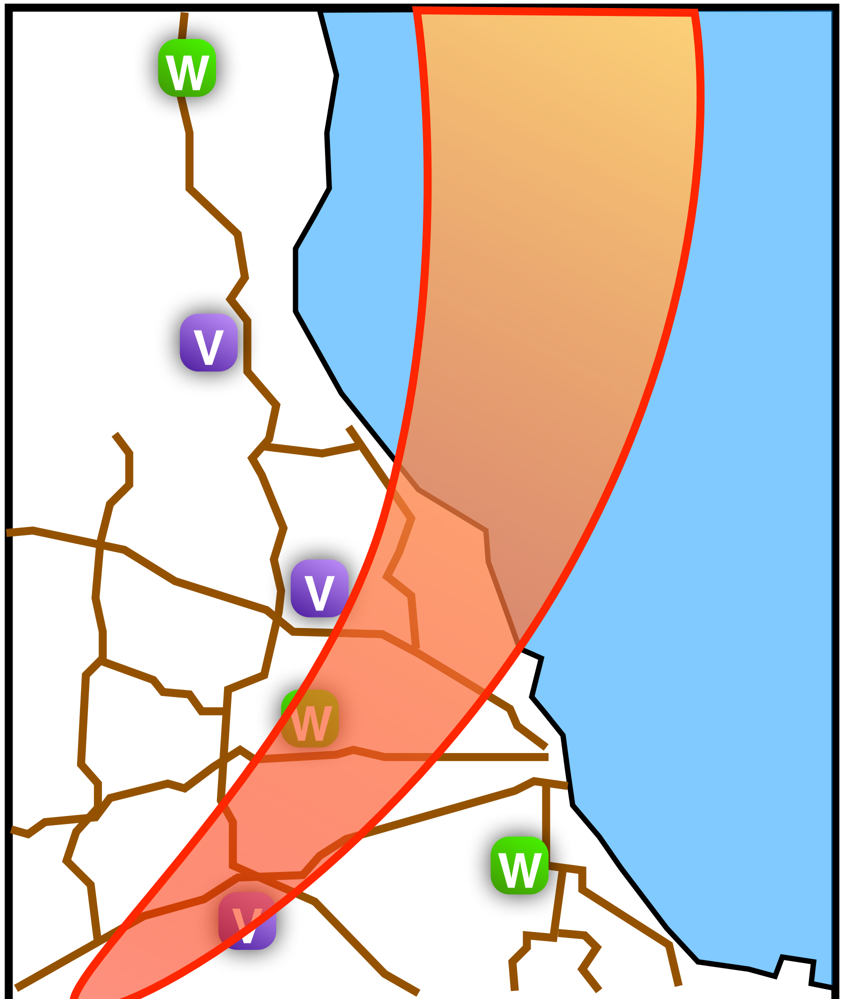
Transportation and Storage



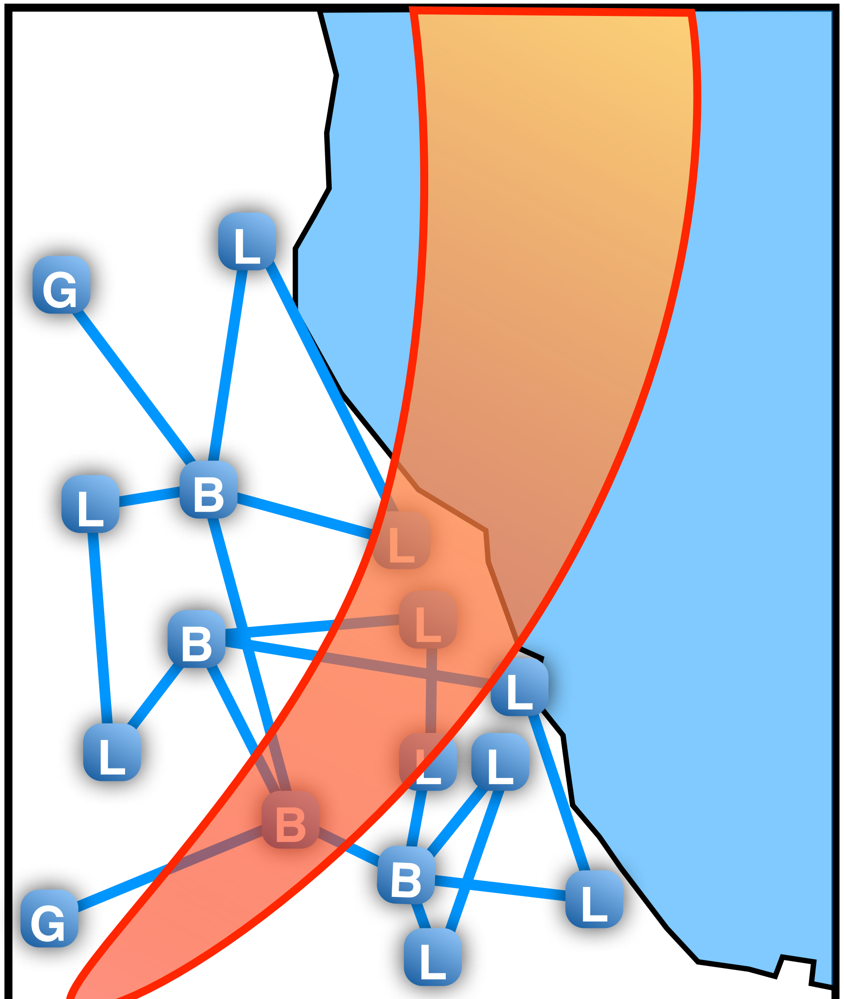
Power System

What do we know?

Threat Simulation



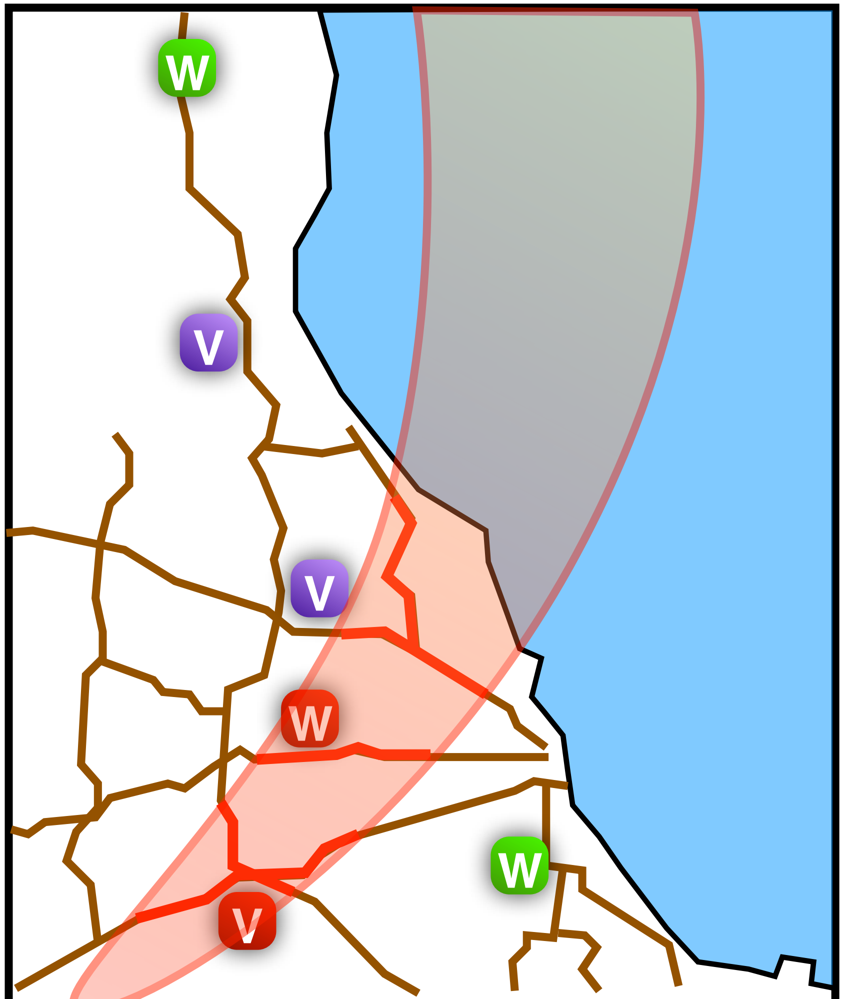
Transportation and Storage



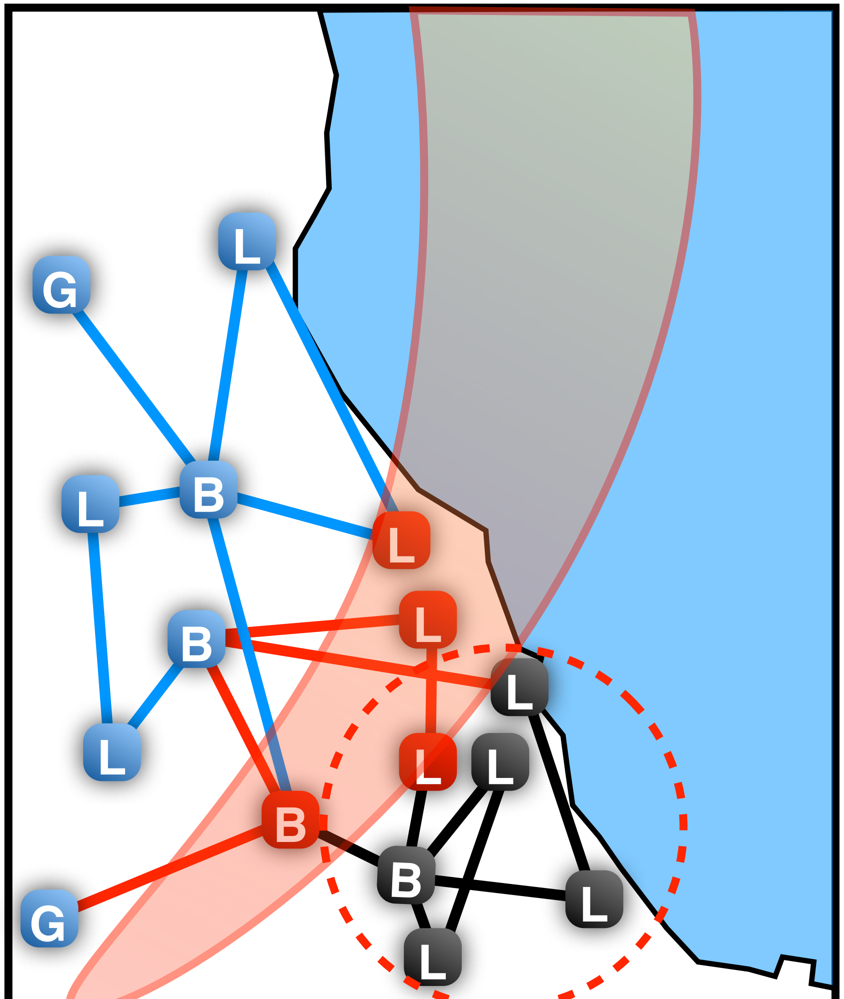
Power System

What do we know?

Fragility Simulation

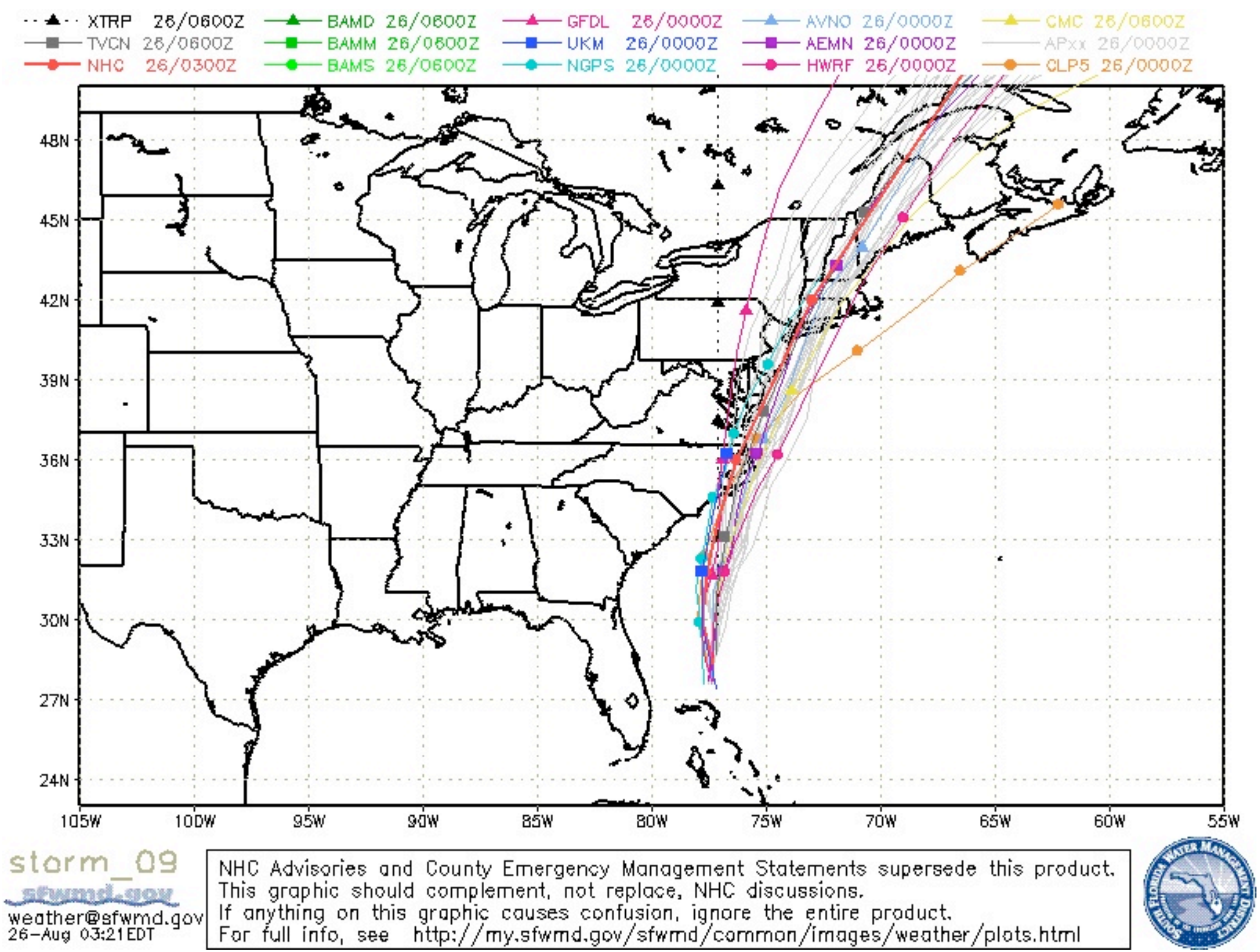


Transportation and Storage

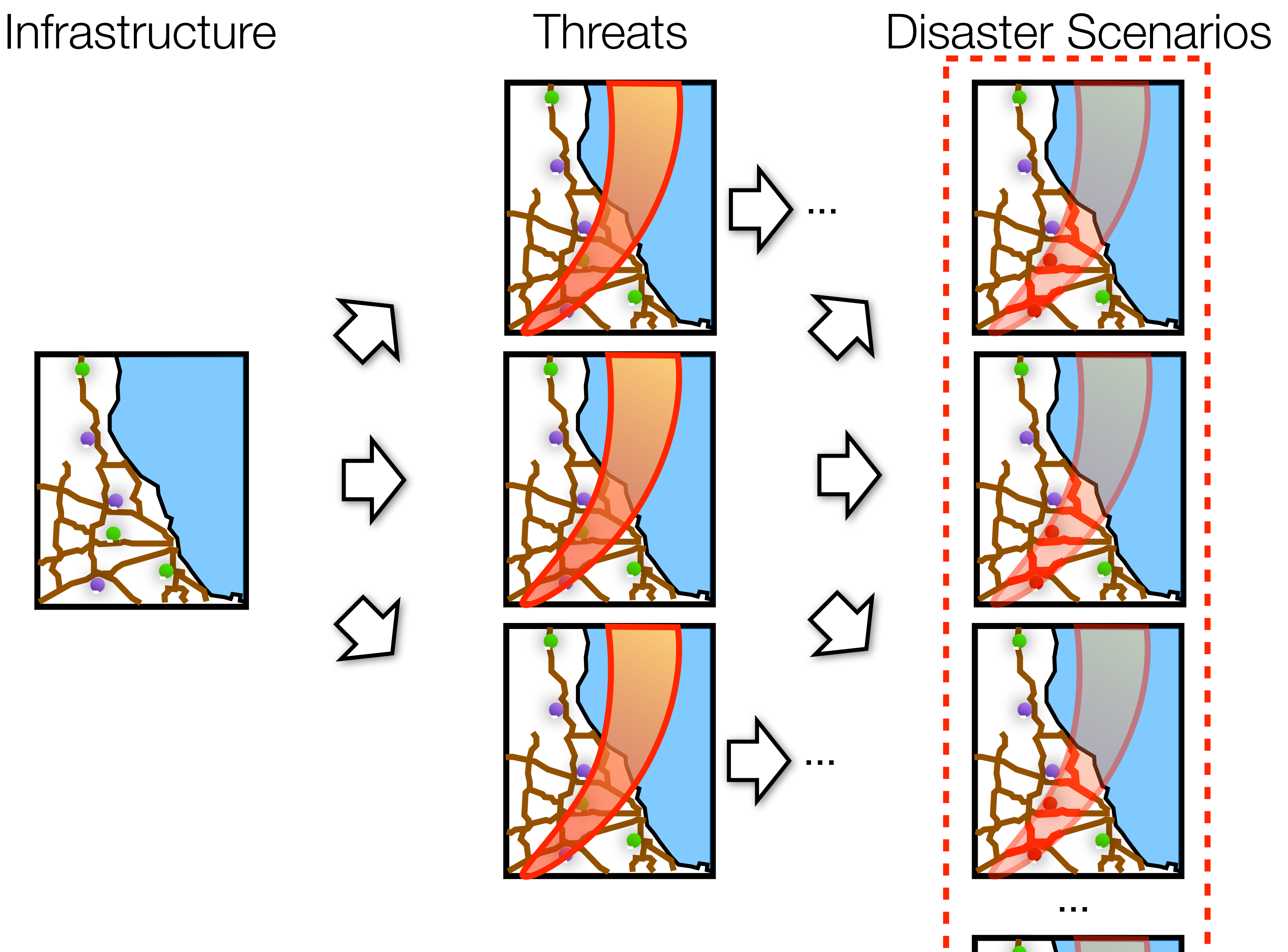


Power System

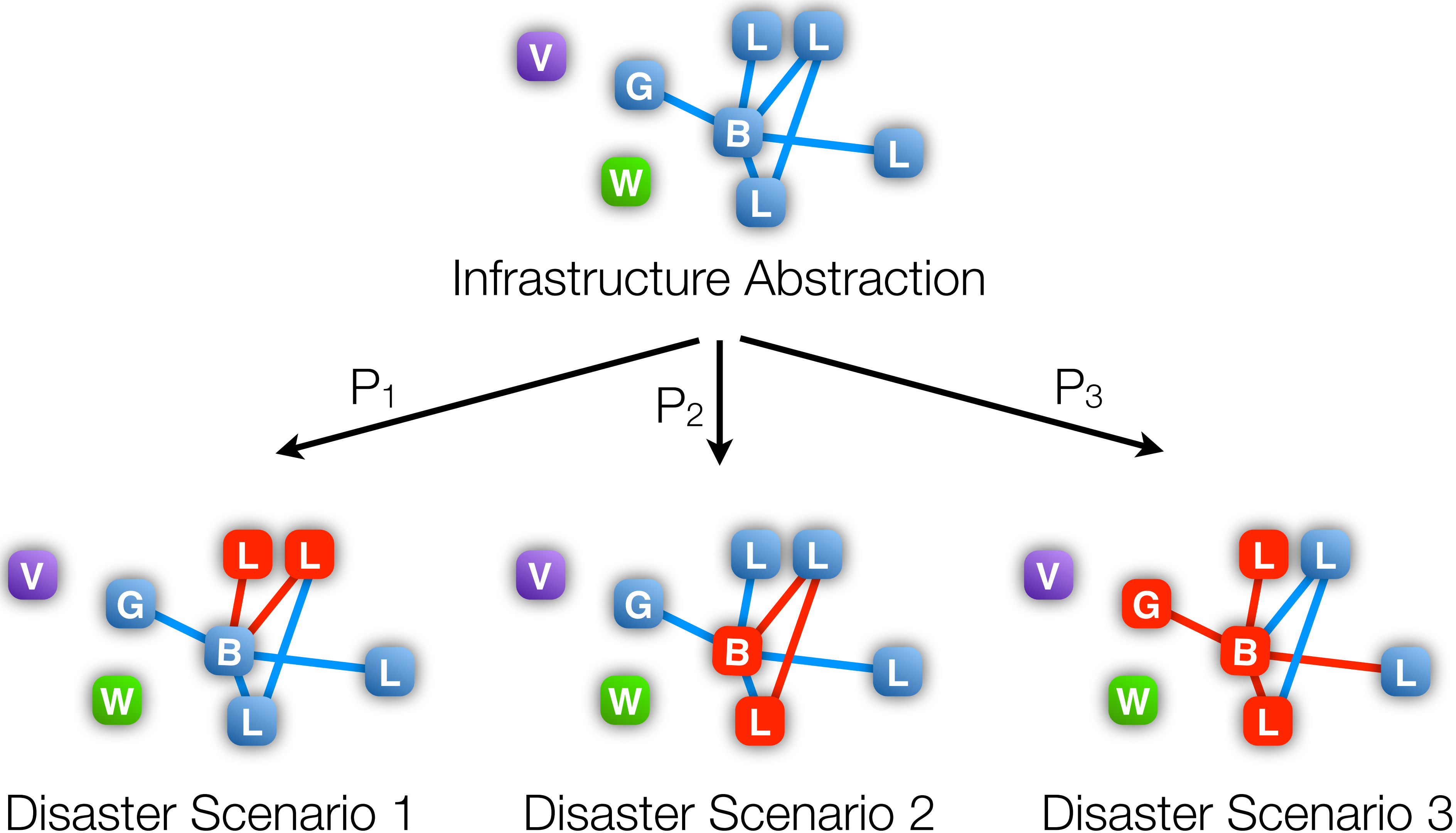
Stochasticity of Threats (Hurricane Case Study)



Stochasticity of Threats



2-Stage Stochastic Damage Model



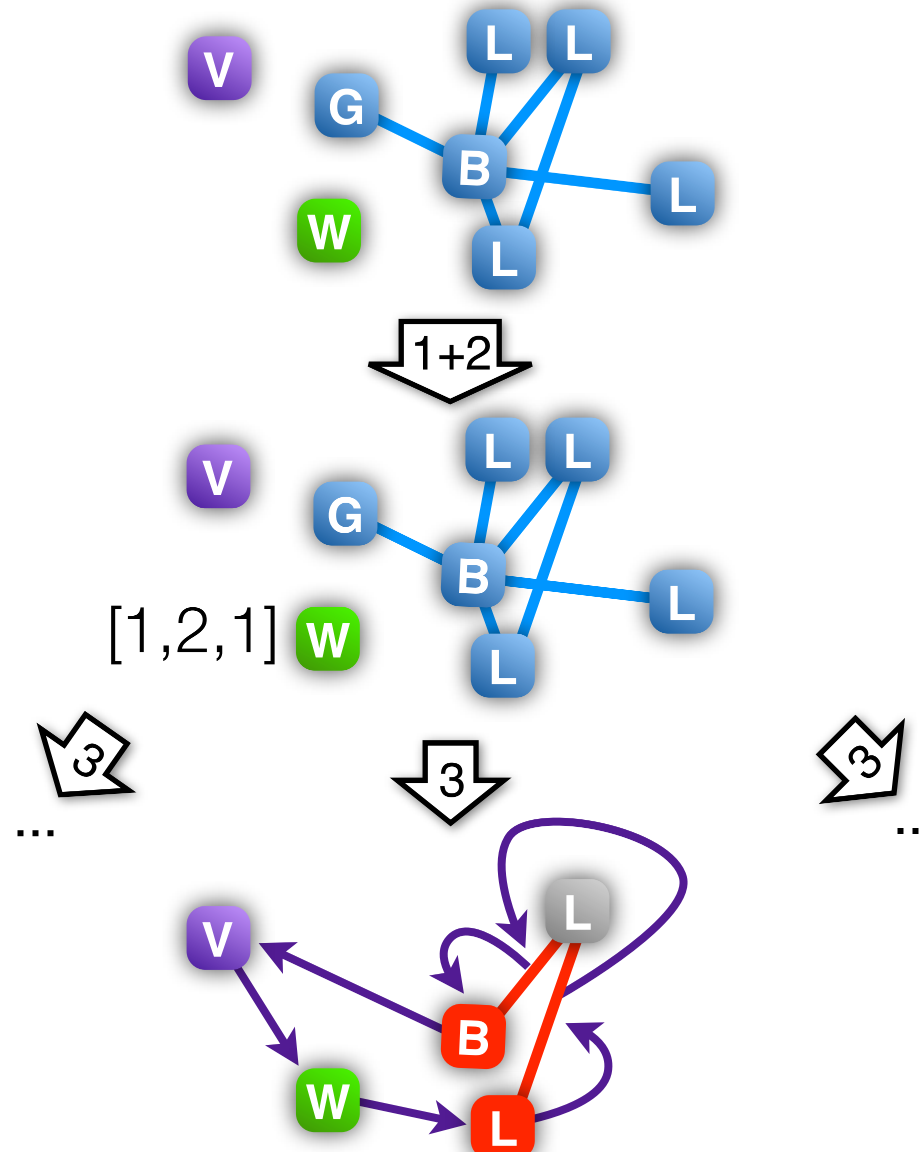
Disaster Recovery - Decisions

1. Where to store recovery supplies

2. How much of each component to stockpile

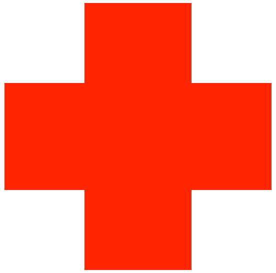
3. Given a particular disaster,

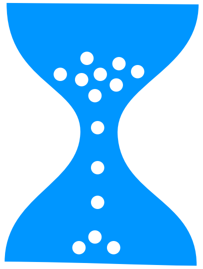
    - A fast recovery plan



Disaster Recovery - Objective

- Over all predicted disasters
  - Minimize
    - Unsatisfied Power (welfare)
    - Restoration Time (distance)
    - Preparation Costs (money)





Disaster Recovery - Given Data

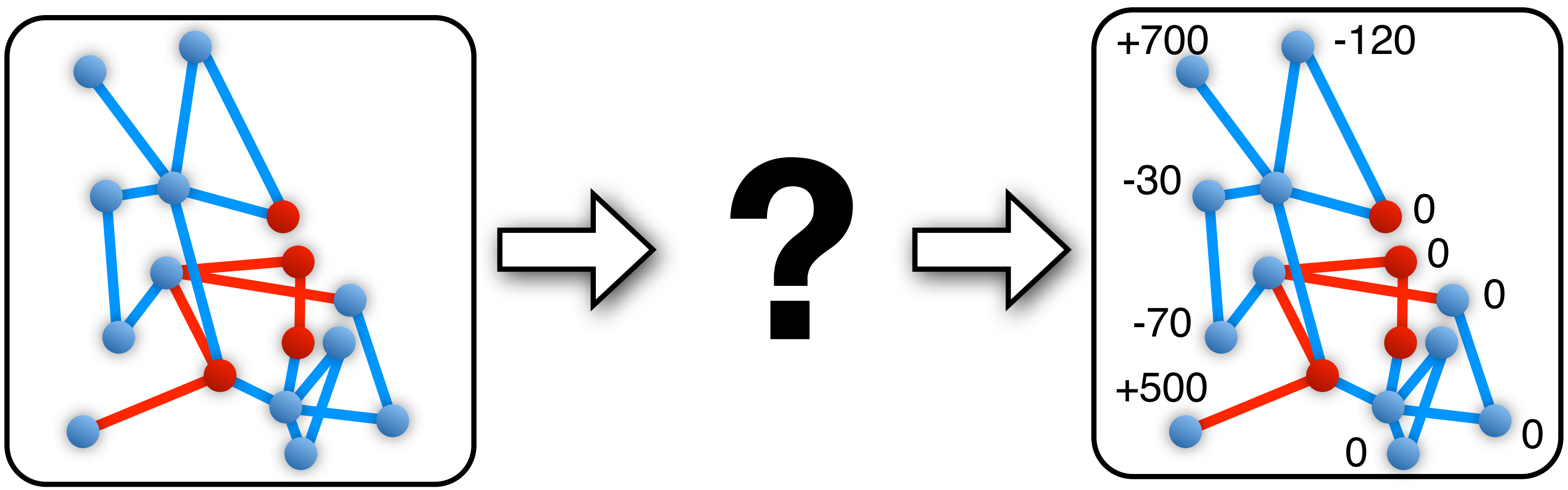
- Warehouses (storage capacity)
- A fixed-size vehicle fleet (storage capacity)
- A stochastic set of disaster scenarios, each with,
    - Destroyed power system components (repair times)
    - Point-to-point travel times

Problem Formulation : Modeling Infrastructure

Power System Case Study

Disaster Recovery - Objective (Revisited)

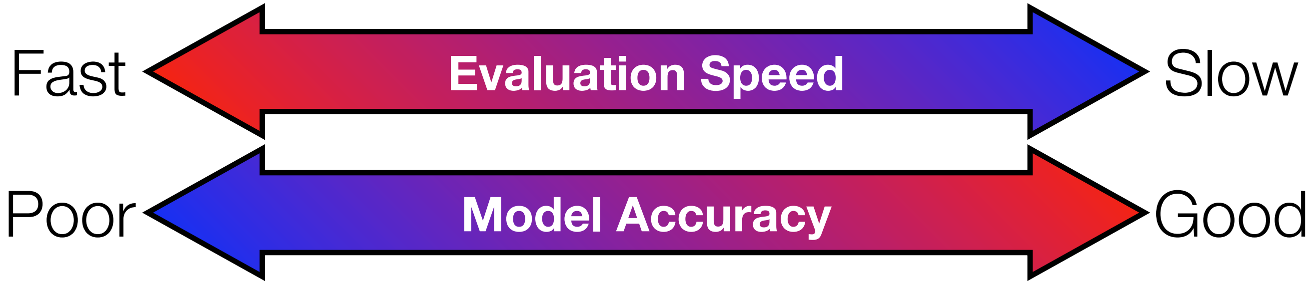
- Over all predicted disasters
  - Minimize
    - Unsatisfied Power (welfare)
    - ...



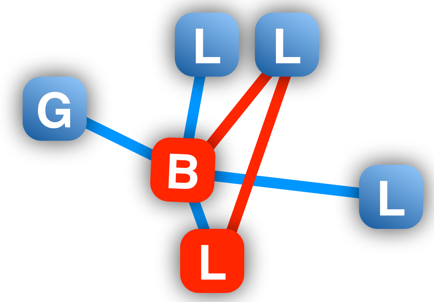
Modeling Infrastructure Systems

- Models of infrastructure systems are an **approximation** of a real-world system.
- The models are only as accurate as the physical assumptions they make. (e.g. Newtonian Physics vs Einsteinian Physics)

	Steady State				Transient	
Model	Connectivity	Max Flow	Potential Flow	Non-Linear Flow	Transient Flow	Physical Model
Evaluation Algorithm	SSC	Edmonds Karp	Gaussian Elimination	Newton Raphson	Newton Raphson	The Universe



Models of Static Power Systems



How many demands are met?

Connectivity

Max Flow

$$P_i = \sum_{\langle i,j \rangle \in E} f_{ij}$$

Potential Flow (DC Model)

$$P_i = \sum_{k=1}^{n} b_{ik}(\theta_i - \theta_k)$$

Non-Linear Flow

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

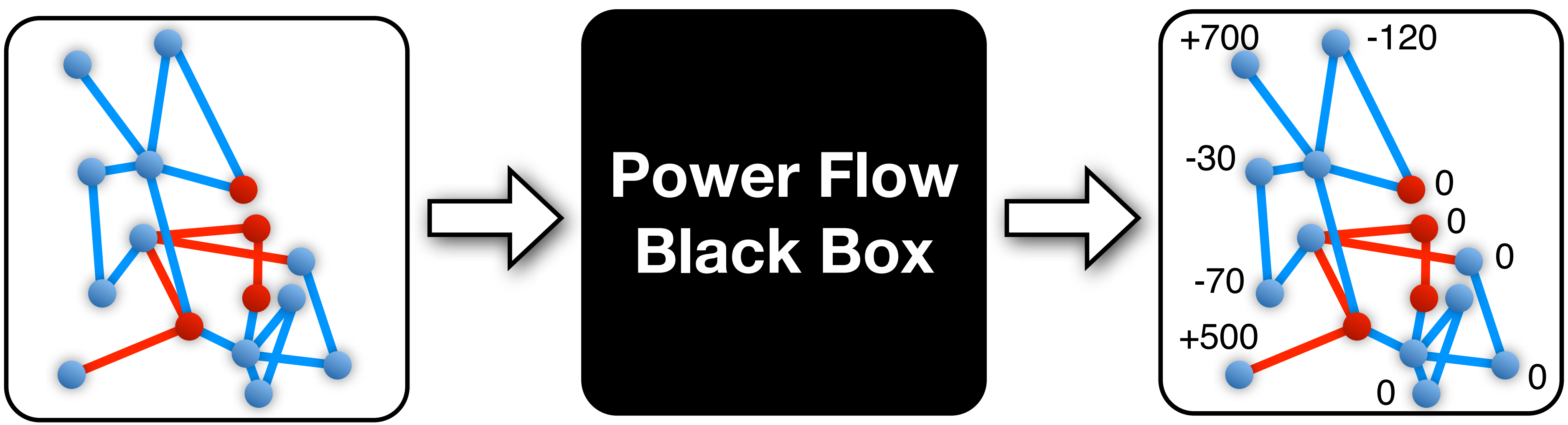
$$Q_i = \sum_{k=1}^{n} |V_i||V_k|(g_{ik}\sin(\theta_i - \theta_k) + b_{ik}\cos(\theta_i - \theta_k))$$

Static Power Models for Optimization

- Approach 1: Work with the highest quality linear model (DC Flow)

$$P_i = \sum_{k=1}^{n} b_{ik}(\theta_i - \theta_k)$$

- Approach 2: Develop algorithms that see the power model as a "black-box" and are power model independent



$$\text{DemandsMet}(\mathcal{PN}, \mathcal{DS})$$

Optimizing Power Systems is Tricky

- The DC Flow and richer models all exhibit **Braess's paradox**

$$P_i = \sum_{k=1}^{n} b_{ik}(\theta_i - \theta_k)$$

Braess's Paradox

"...adding extra capacity to a network when the moving entities selfishly [least resistance] choose their route, can in some cases reduce overall performance" [wikipedia]

Braess's Paradox Example: Input

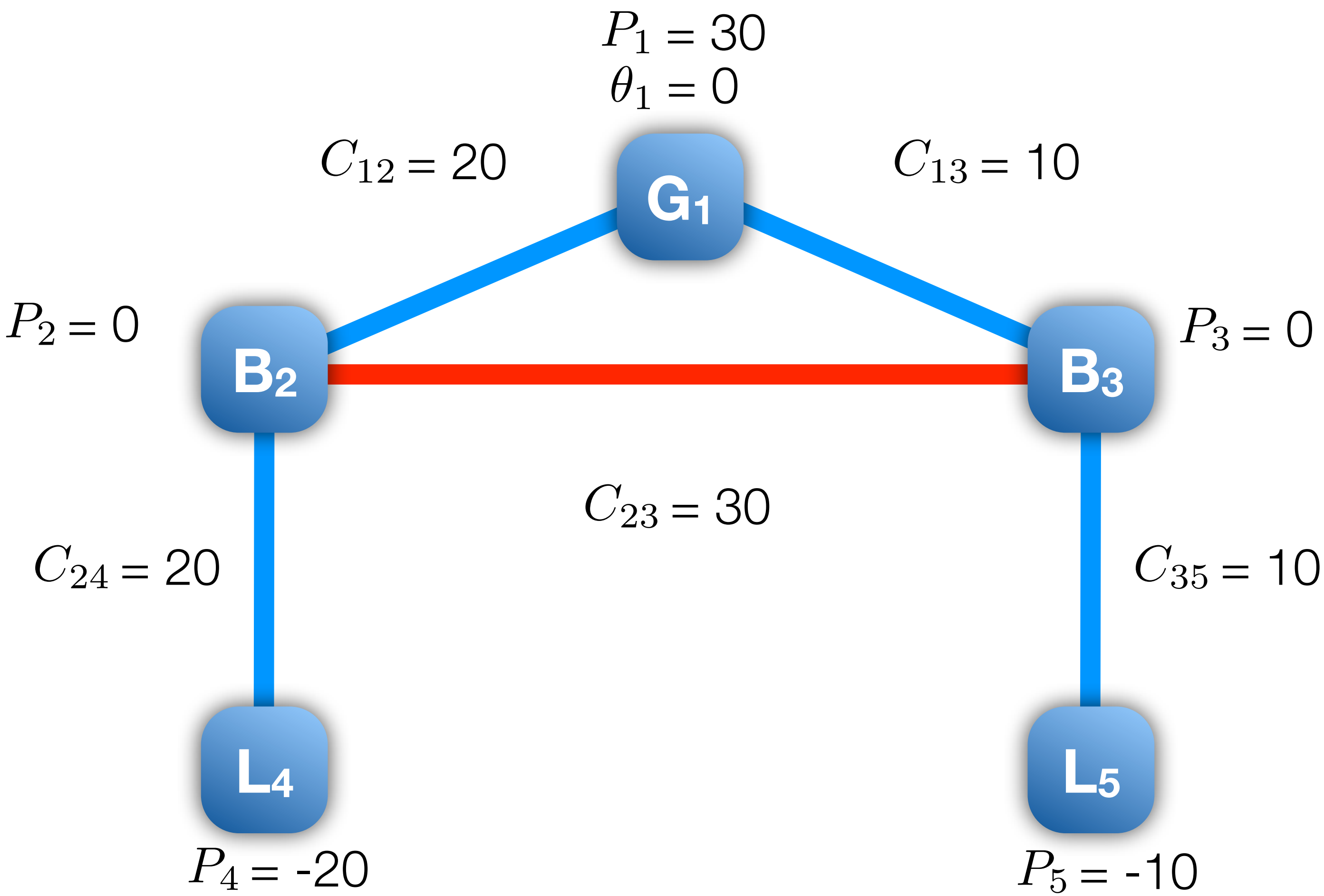
DC Power Flow

$$P_i = \sum_{k=1}^{n} P_{ik}$$

$$P_{ik} = b_{ik}(\theta_i - \theta_k)$$

$$b_{ik} = 1$$

$$P_{ik} = (\theta_i - \theta_k)$$



θ - Phase Angle

P - Power

b - Susceptance

C - Capacity

[Bienstock'07]

Braess's Paradox Example : Damaged Solution

DC Power Flow

$$P_i = \sum_{k=1}^{n} P_{ik}$$

$$P_{ik} = b_{ik}(\theta_i - \theta_k)$$

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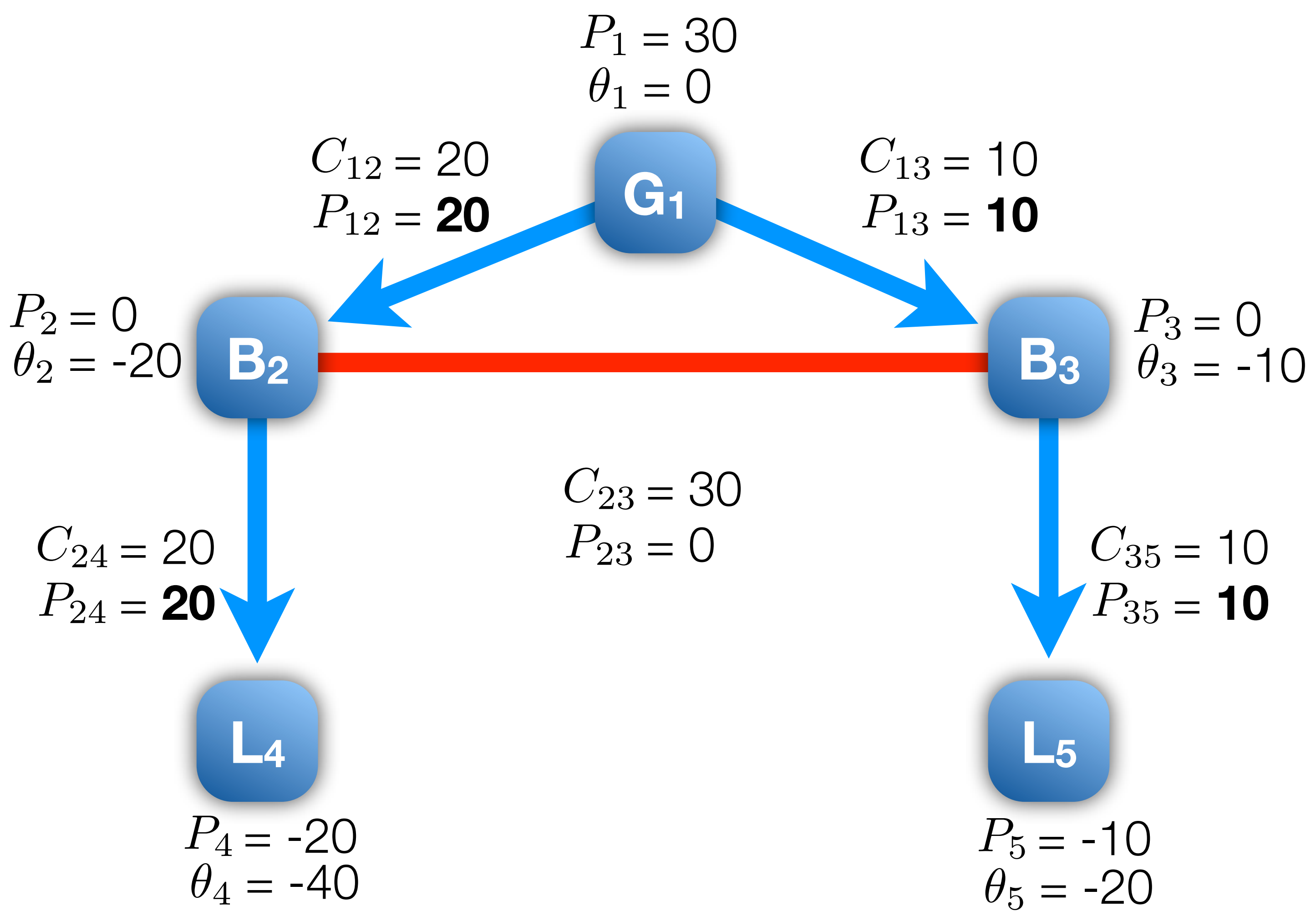

Power Served: **30**

Braess's Paradox Example: Repaired

DC Power Flow

$$P_i = \sum_{k=1}^{n} P_{ik}$$

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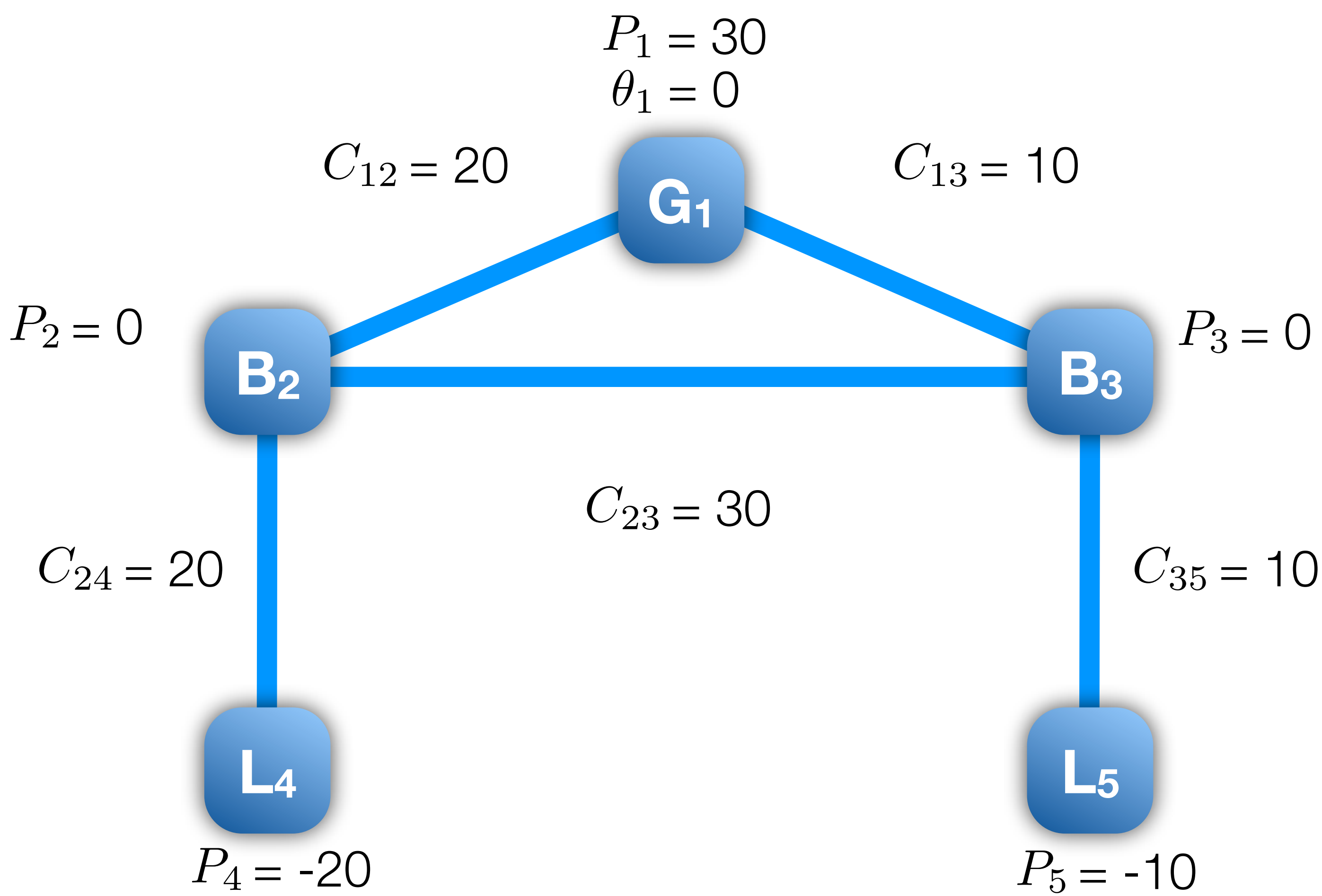

θ - Phase Angle

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[Bienstock'07]

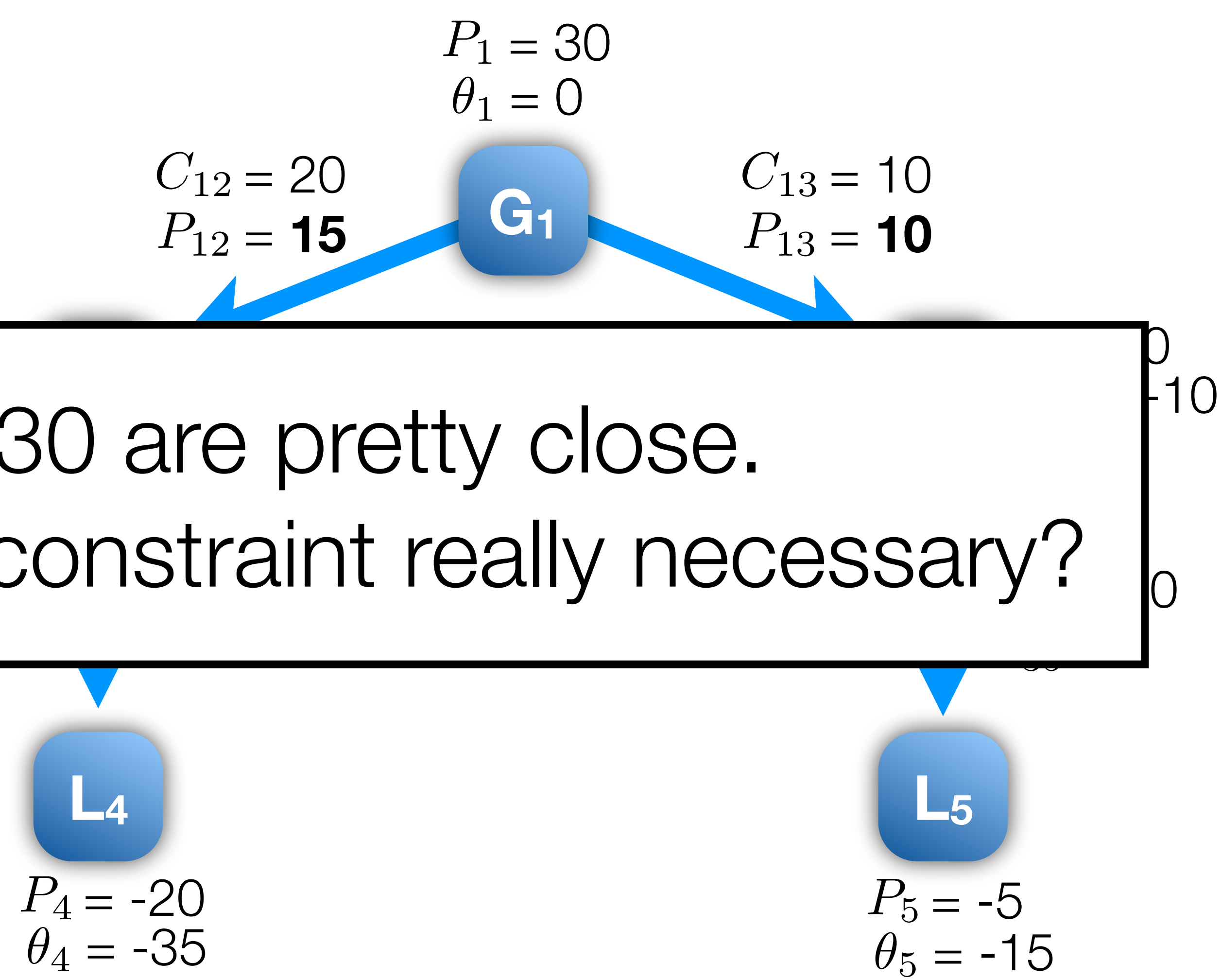
Braess's Paradox Example : Repaired Solution

DC Power Flow

$$P_i = \sum_{k=1}^{n} P_{ik}$$

$$P_{ik} = b_{ik}(\theta_i - \theta_k)$$

25 and 30 are pretty close.
Is this capacity constraint really necessary?



θ - Phase Angle

P - Power

b - Susceptance

C - Capacity

Power Served: **25**

[Bienstock'07]

Braess's Paradox Example : Ignoring Capacities

DC Power Flow

$$P_i = \sum_{k=1}^{n} P_{ik}$$

$$P_{ik} = b_{ik}(\theta_i - \theta_k)$$

$$b_{ik} = 1$$

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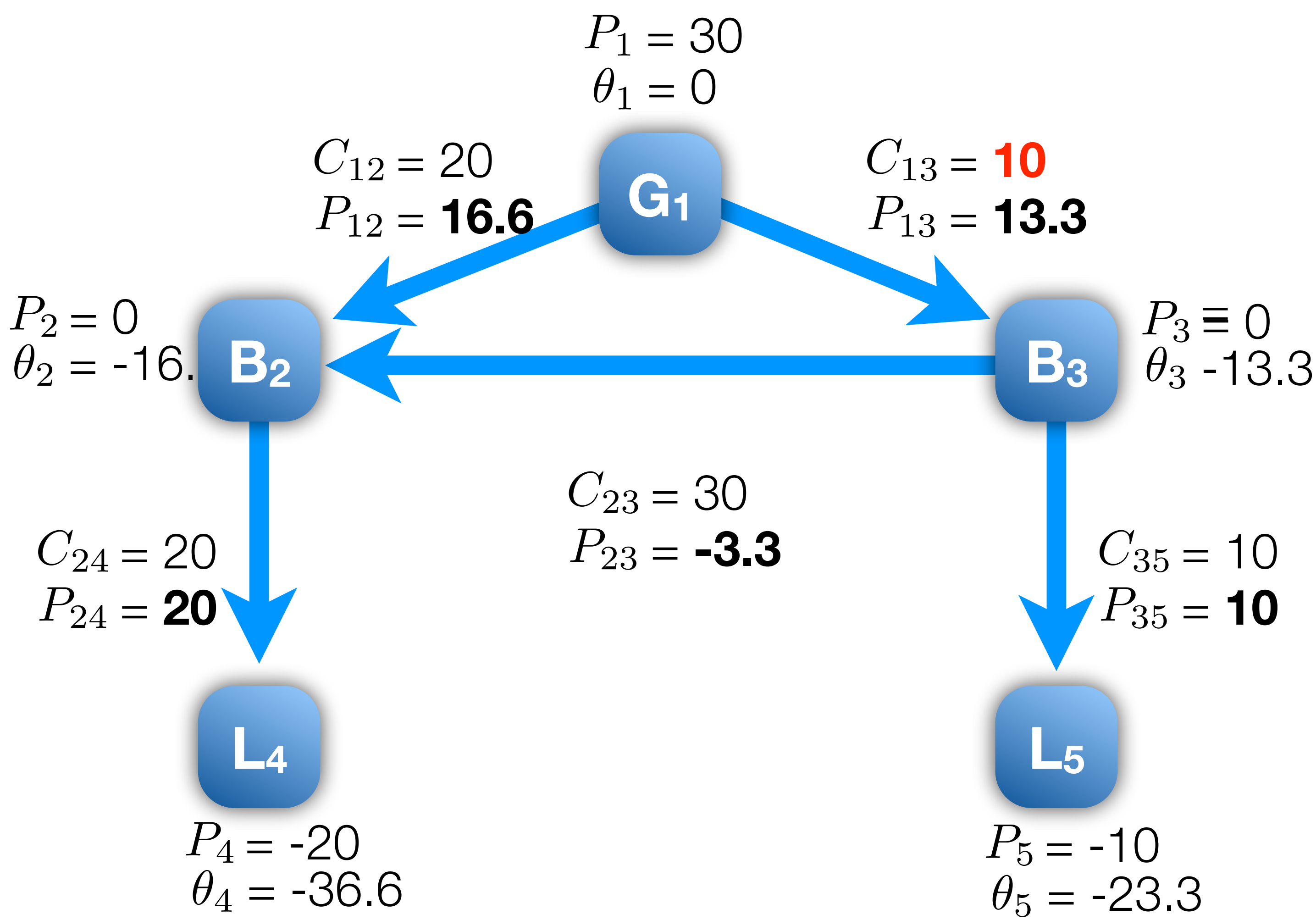

Power Served: **30**

θ - Phase Angle

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[Bienstock'07]

Braess's Paradox Example : Ignoring Capacities

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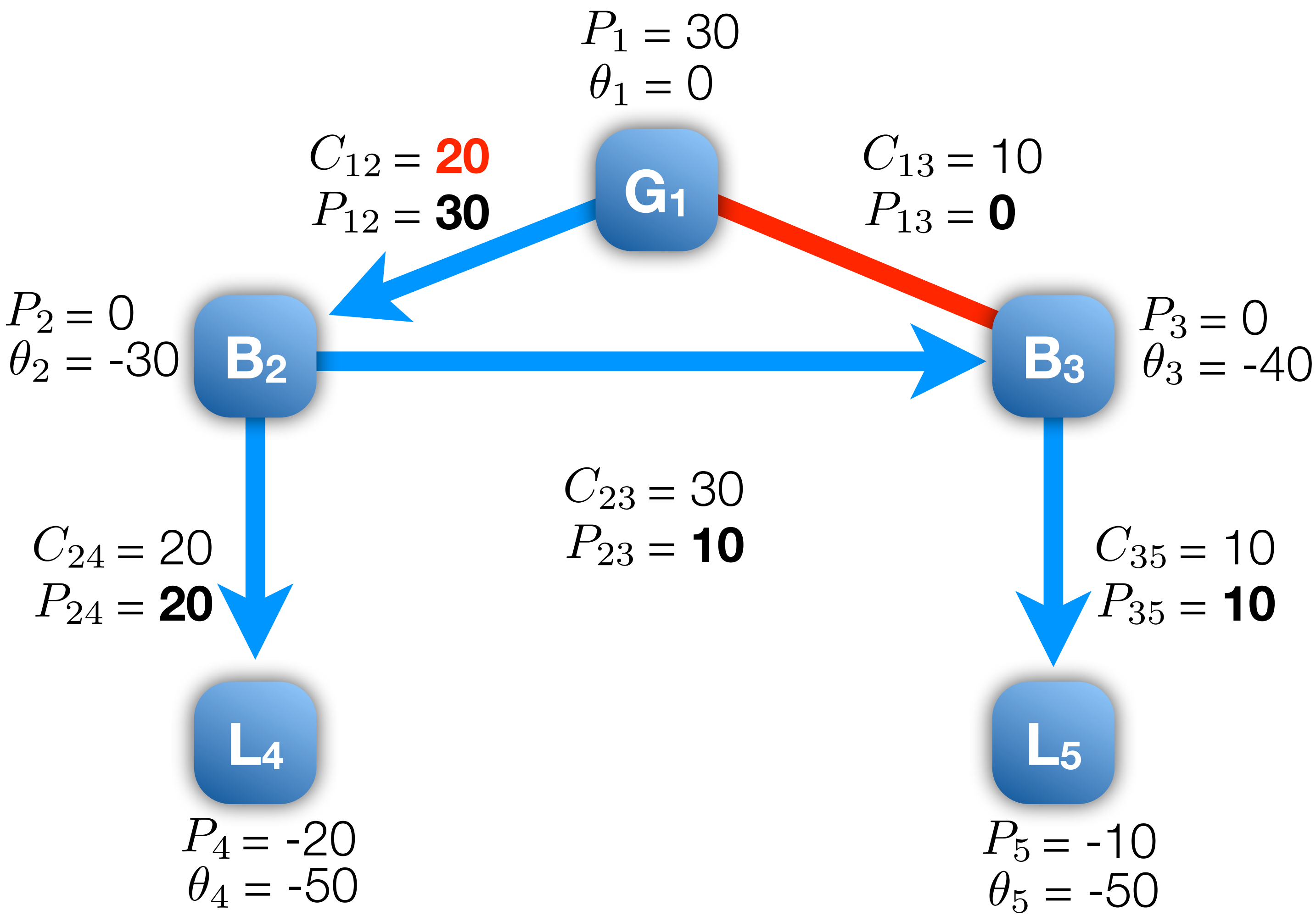

Power Served: **30**

[Bienstock'07]

Braess's Paradox Example : Ignoring Capacities

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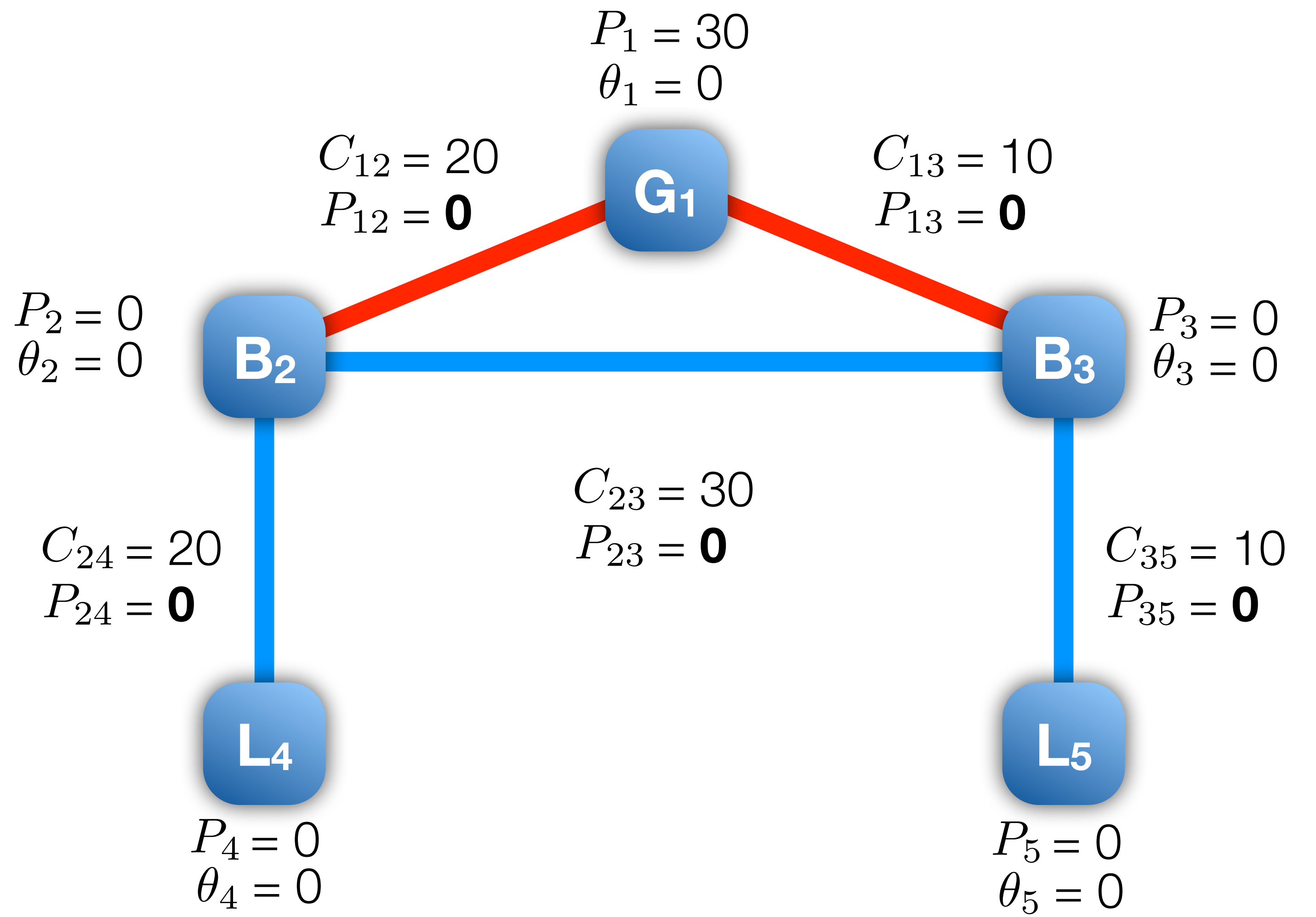


θ - Phase Angle

P - Power

b - Susceptance

C - Capacity

Power Served: **0**

[Bienstock'07]

Overview

- Motivation
- Problem Formulation
  - Modeling Infrastructure Networks
- Basic Approach
  - Stochastic Storage Problem
  - Restoration Routing Problem
  - Combined Results
- Future Work

The Basic Approach

Disaster Recovery (Review)

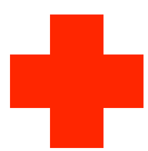
1. Where to store recovery supplies

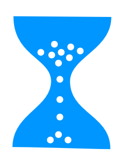
2. How much of each component to stockpile

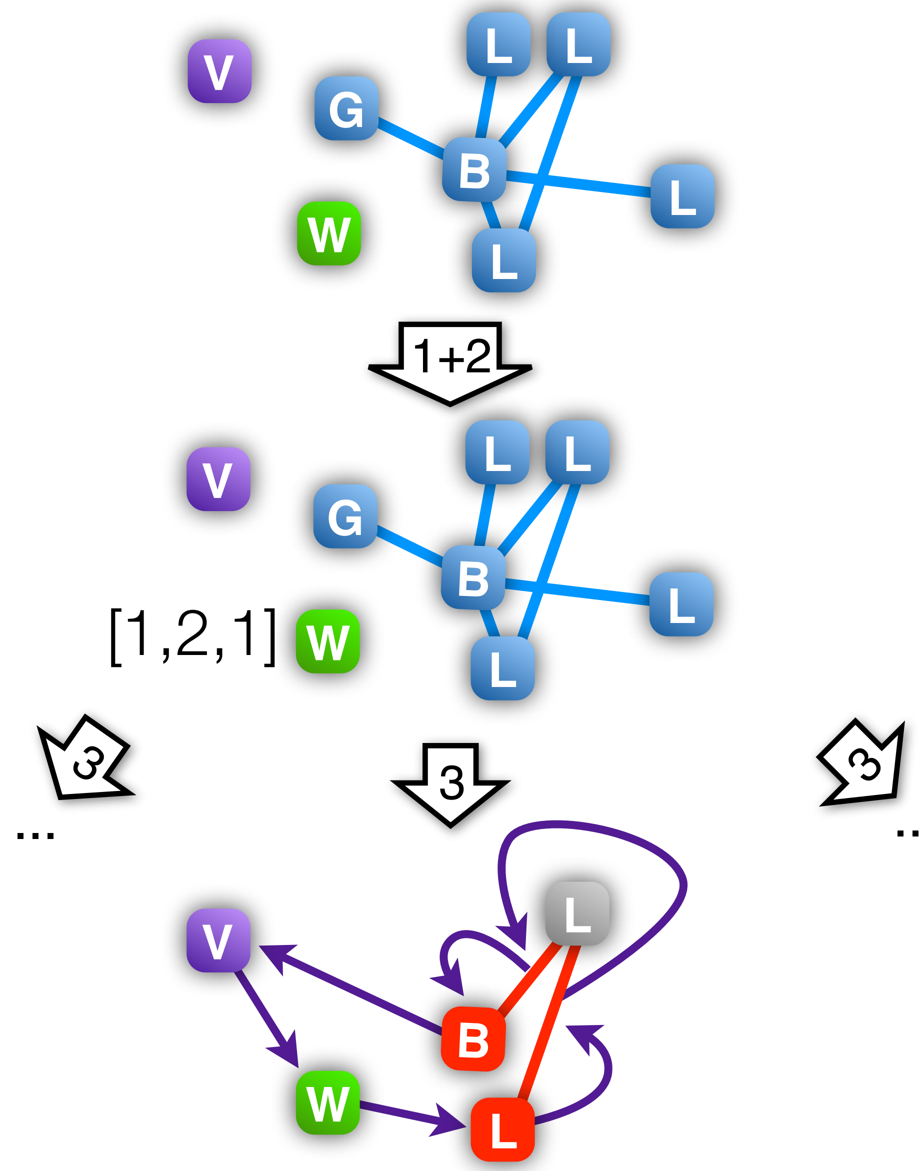
3. Given a particular disaster,

- A fast recovery plan

Objective: Minimize

Unsatisfied Power (welfare) 

Restoration Time (distance) 



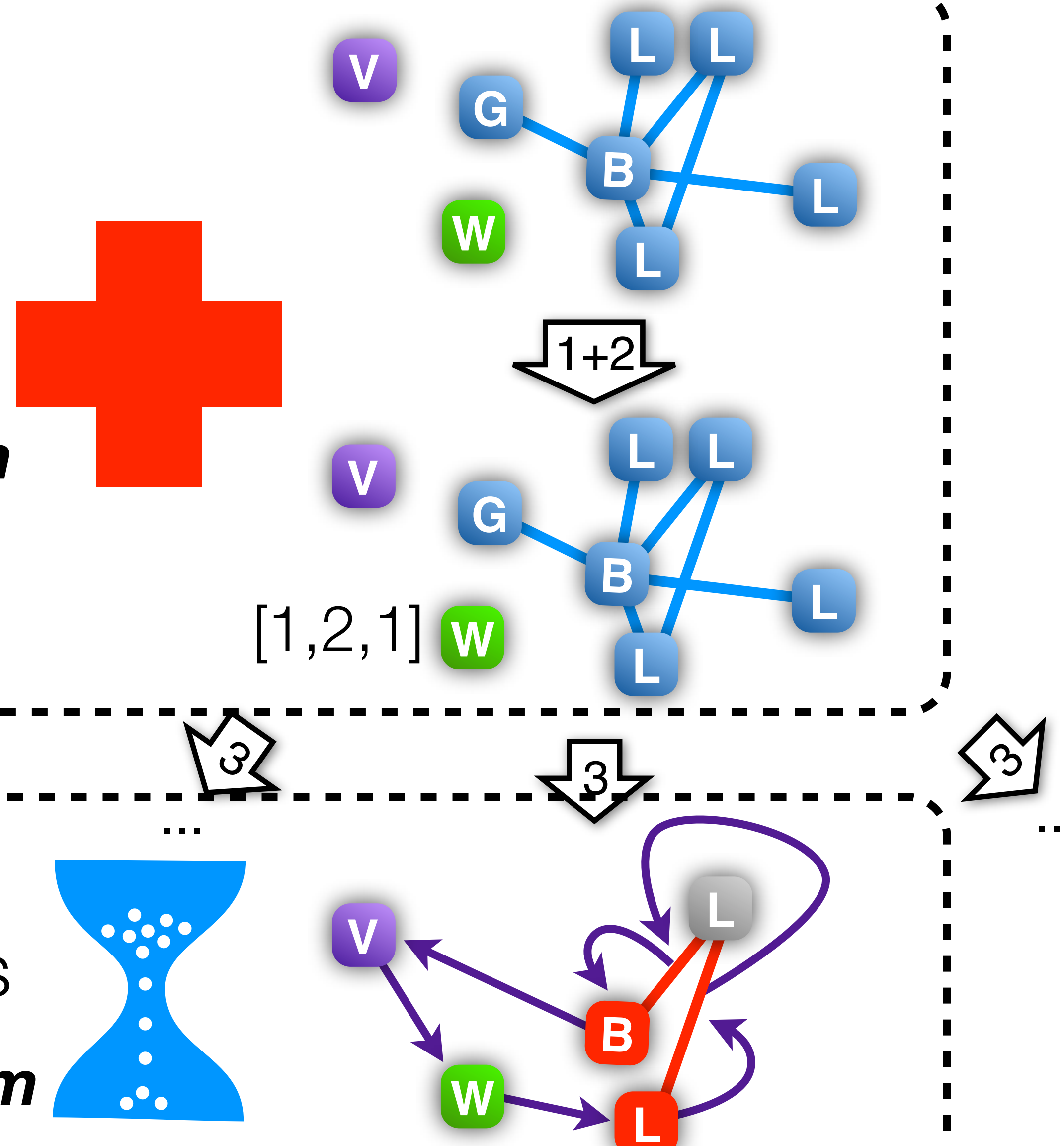
Disaster Recovery - Basic Approach

Preparation Decisions

Stochastic Storage Problem

Disaster Specific Decisions

Restoration Routing Problem



A Note on Optimization Paradigms

Optimization Paradigms

- Mixed Integer Programming (**MIP**)
  - Pros: Optimality Proof, Supports Linear DC Power Model
  - Cons: Only supports Linear Equations, Not Effective for Routing

- Constraint Programming (**CP**)
  - Pros: Optimality Proof, Combinatorial Constraints, Good for Routing
  - Cons: Least Scaleable, Braess's Paradox makes Power Networks Difficult in CP

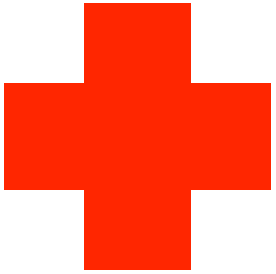
Optimization Paradigms (Continued)

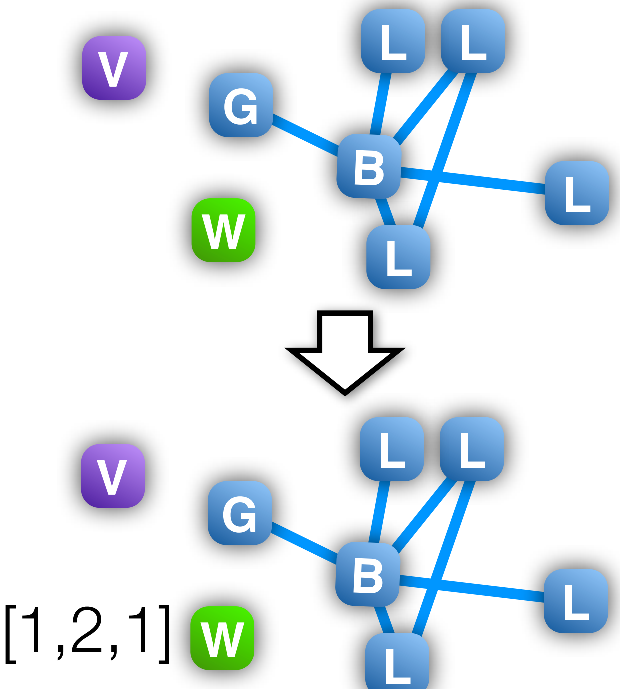
- Local Search (**LS**)
  - Pros: Most Scaleable, Can integrate “Black-Box” power model
  - Cons: No Quality Guarantees, Often Heuristic Based

- Large Neighborhood Search (**LNS**)
  - Pros: Combines the strength of CP with the scaleability of LS, Very effective for Scaling Routing Problems
  - Cons: No Quality Guarantees, Same Difficulties Faced by CP for Power Network Modeling

Stochastic Storage Problem

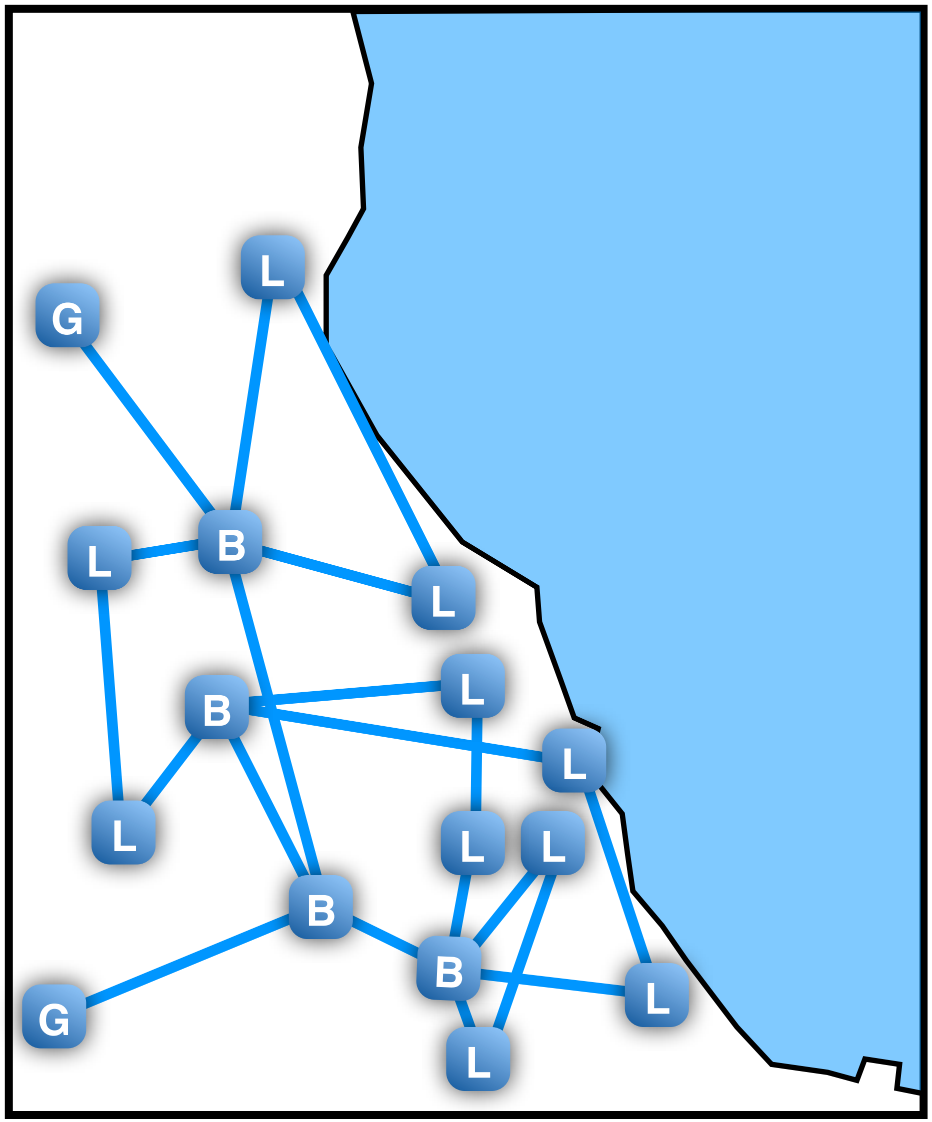
Preparation
Storage Decisions

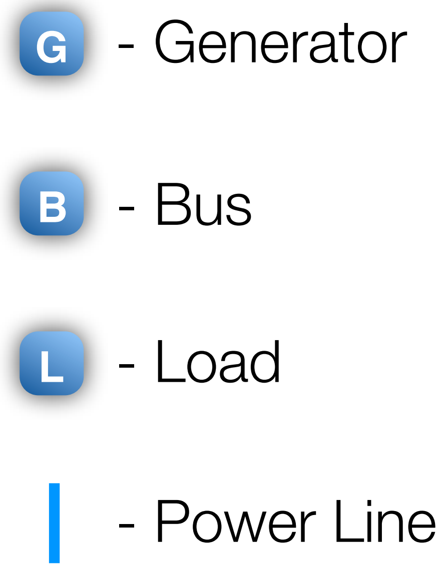




See: **Strategic Stockpiling of Power System Supplies for Disaster Recovery.** C. Coffrin, P. Van Hentenryck, and R. Bent. (PES 2011)

Power System

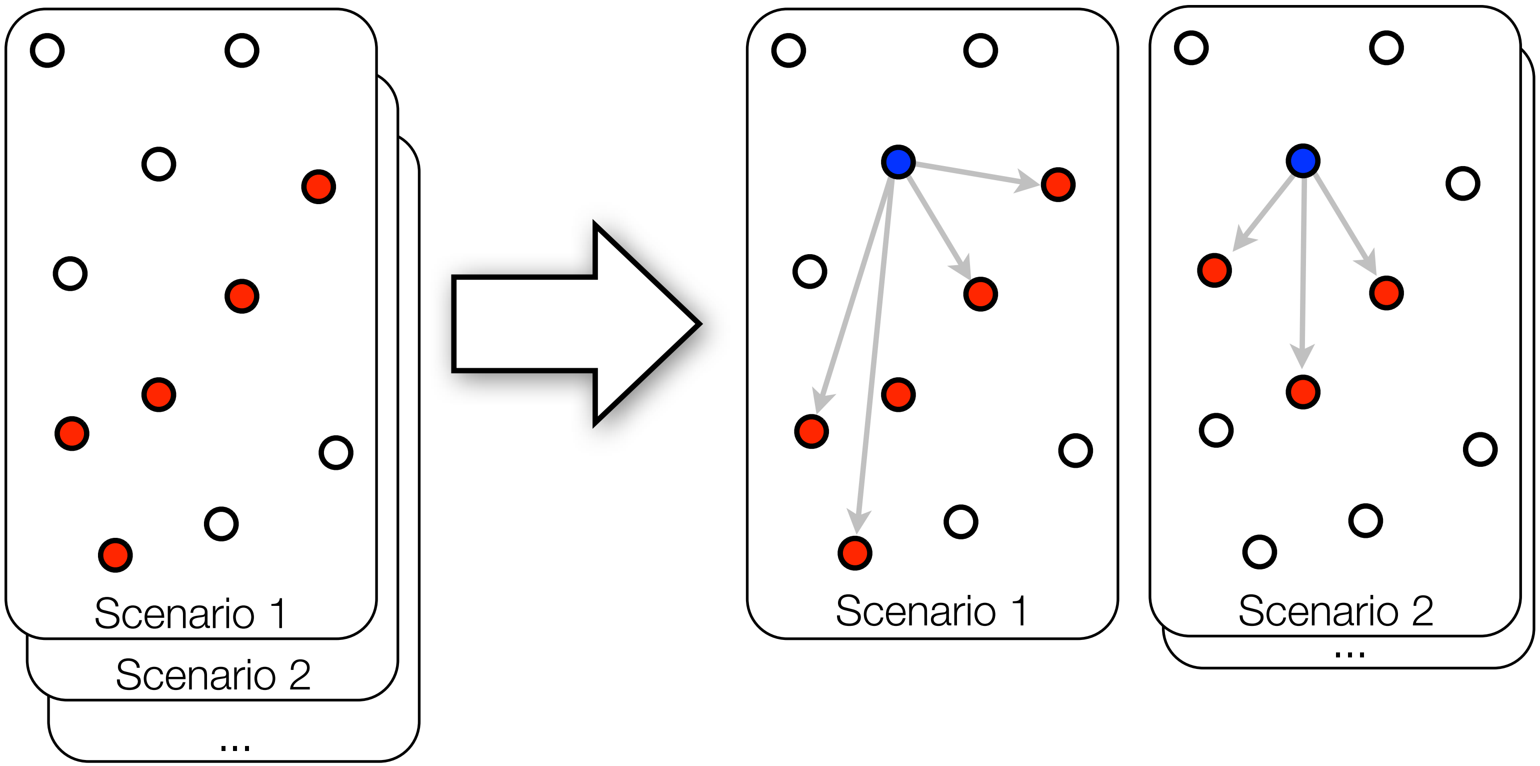




Quantities of each component to store are the preparation decisions.

Which items they fix are disaster specific the decisions.

The Stochastic Storage Problem



Maximize: Sum(s in Scenarios) Pr_S*$Flow_S$

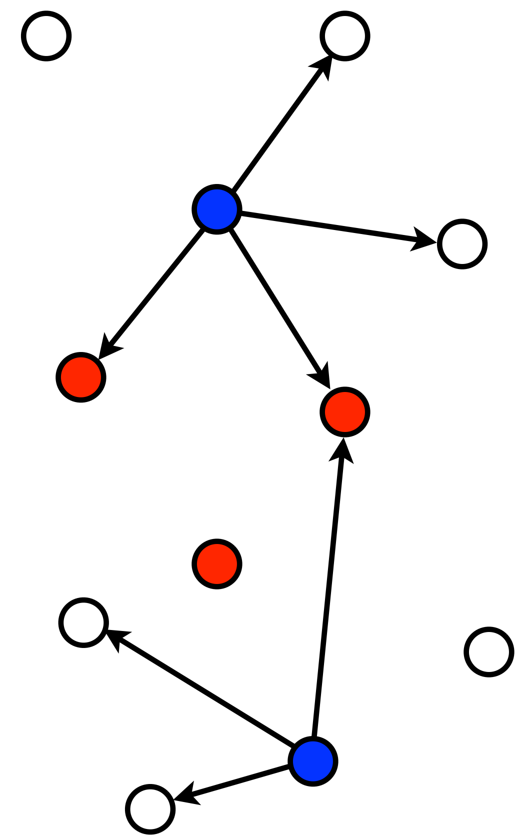
Stochastic Storage Solution Approaches

- Mixed Integer Programming (MIP)
  - Globally Optimal
  - Linear DC Power Model Only
  - Limited Scalability

- Configuration Generation (LS + MIP)
  - No Quality Guarantee
  - Better Scalability
  - Power Model Independent

Stochastic Storage Model (MIP)

- For Every Component type, t, (1st Stage)
  - **UnitsStored**$_t$ (0,Capacity)
- For Every Scenario, s, (2nd Stage)
  - **Flow**$_s$ (0,MaxFlow)
  - **Repaired**$_{s,i}$ {0,1}
- Objective:
  - Maximize: sum(s in Scenario) Pr_s***Flow**$_s$



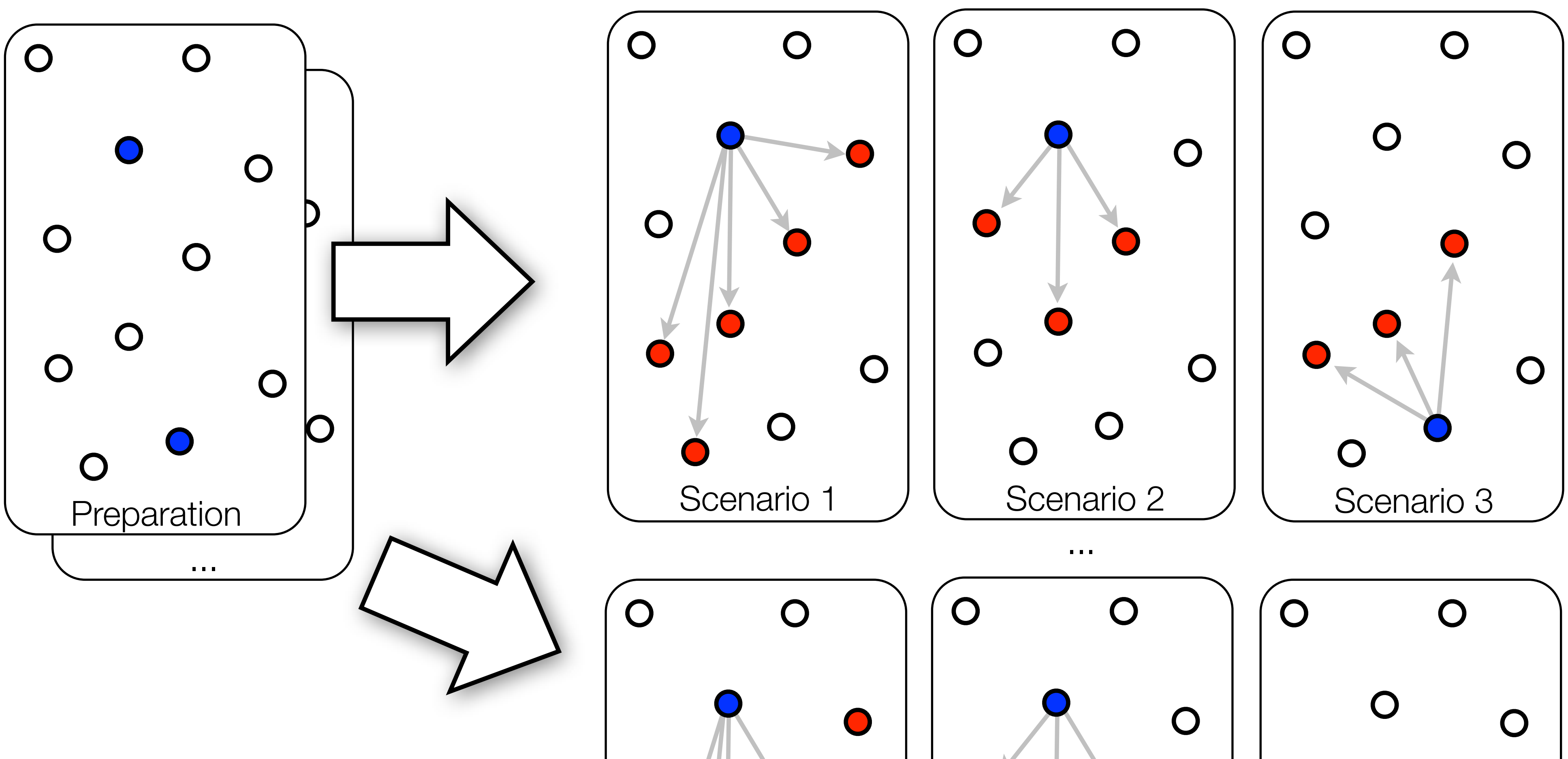
Stochastic Storage Model (MIP)

- For Every Component type, t, (1st Stage)
  - **UnitsStored**$_t$ (0,Capacity)
- For Every Scenario, s, (2nd Stage)
  - **Flow**$_s$ (0,MaxFlow)
  - **Repaired**$_{s,i}$ {0,1}

- Maximize: sum(s in Scenario) Pr_s * **Flow**$_s$
- Subject To:
  - **UnitsStored**$_t$ cannot exceed the storage capacity
  - For every Scenario, s,
    - **Flow**$_s$ determined by a Linear DC Model using which items are **Repaired**$_{s,i}$
    - For every Type, t,
      - **Repaired**$_{s,i}$ items of type, t, cannot exceed **UnitsStored**$_t$

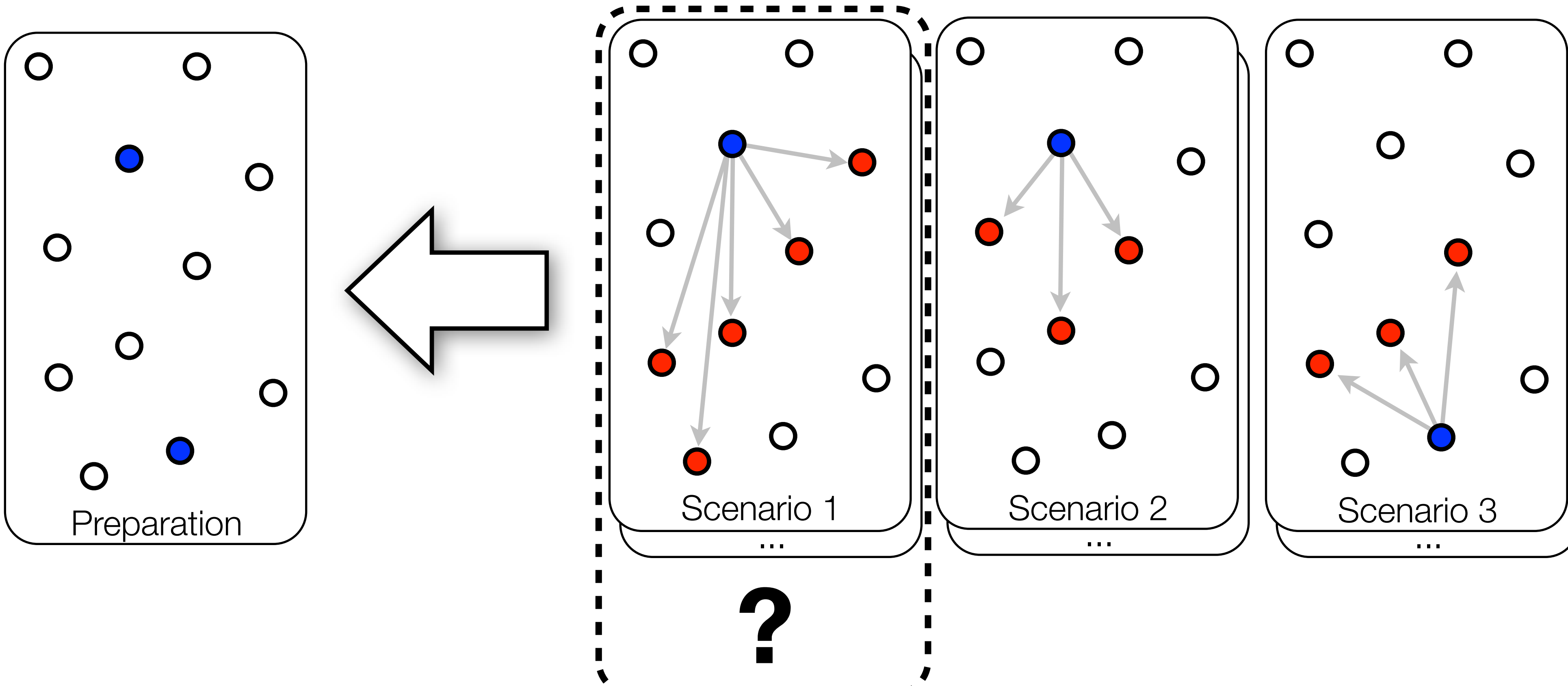
The Stochastic Storage Problem (MIP)

- Stochastic Storage MIP Model is “top-down”
  - Given stored items: What things should be repaired in each scenario?



The Stochastic Storage Problem (in reverse)

- What about a "bottom-up" approach?
  - Given good restoration plans for each scenario: Can the scenarios agree on a which items to store? (i.e. Configuration Generation)



Collection of What-If Simulations

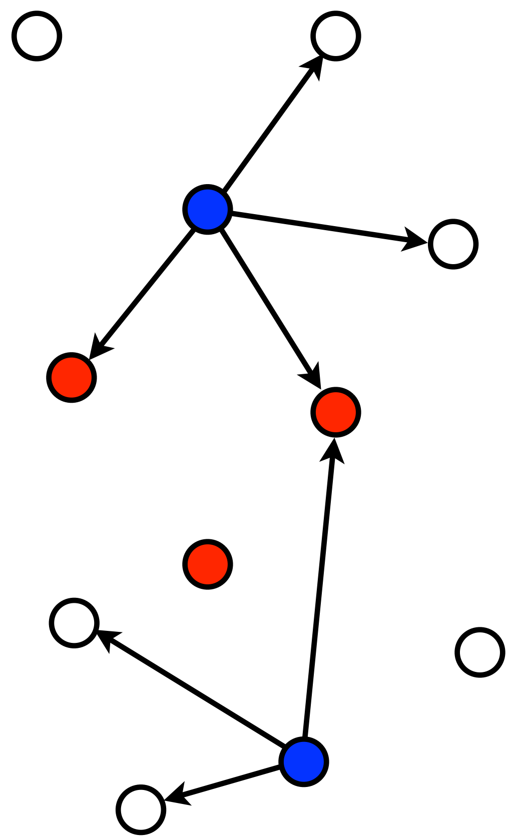
Scenario 1

Scenario 2

Scenario 3					
Gen	Bus	Line	Tran	Flow	
1	0	0	0	1243	Config 1
0	1	0	0	1200	Config 2
1	1	1	0	1322	Config 3
1	1	2	0	1400	Config 4
...	...	...	...	...	Config ...

Configuration Storage Model

- For Every Component type, t, (1st Stage)
  - **UnitsStored**$_t$ (0,Capacity)
- For Every Scenario, s, (2nd Stage)
  - **Flow**$_s$ (0,MaxFlow)
  - **Repaired**$_{s,i}$ {0,1}
  - **ConfigUsed**$_{s,c}$ {0,1}
- Objective:
  - Maximize: sum(s in Scenario) Pr_s * **Flow**$_s$



Configuration Storage Model

- For Every Component type, t, (1st Stage)
  - **UnitsStored**$_t$ (0,Capacity)
- For Every Scenario, s, (2nd Stage)
  - **Flow**$_s$ (0,MaxFlow)
  - **ConfigUsed**$_{s,c}$ {0,1}

- Maximize: sum(s in Scenario) Pr_s*$\textbf{Flow}_s$
- Subject To:
  - **UnitsStored**$_t$ cannot exceed the storage capacity
  - For every Scenario, s,
    - Only one **ConfigUsed**$_{s,c}$ can be selected
    - **Flow**$_s$ is defined by the selected **ConfigUsed**$_{s,c}$
    - For every Type, t,
      - There must be enough **UnitsStored**$_t$ as selected **ConfigUsed**$_{s,c}$ needs

The Key Challenge for Configuration Generation

- Way too many restoration configurations to generate them all...
- There is often contention between scenarios on the type and quantity of stored items
- Can we generate configurations lazily, especially those that help the scenarios agree on a good expected value?
- We use a combination of greedy and regret configuration generation schemes.

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

Configuration Generation: Example

Storage Capacity: **10**

Disaster Scenario 1				
Line	Load	Bus	Gen	Flow
0	0	0	0	3834
4	1	1	1	4161
7	1	1	1	4195

Disaster Scenario 2				
Line	Load	Bus	Gen	Flow
0	0	0	0	4279
4	0	0	0	4292
6	0	0	0	4292

Disaster Scenario 3				
Line	Load	Bus	Gen	Flow
0	0	0	0	3205
4	1	1	1	3556
0	3	3	3	4217

Configuration Generation: Example

Storage Capacity: **10**

Disaster Scenario 1				
Line	Load	Bus	Gen	Flow
0	0	0	0	3834
4	1	1	1	4161
7	1	1	1	4195

Disaster Scenario 2				
Line	Load	Bus	Gen	Flow
0	0	0	0	4279
4	0	0	0	4292
6	0	0	0	4292

Disaster Scenario 3				
Line	Load	Bus	Gen	Flow
0	0	0	0	3205
4	1	1	1	3556
0	3	3	3	4217

Lower Bound: **3773**

Configuration Generation: Example

Storage Capacity: **10**

Disaster Scenario 1				
Line	Load	Bus	Gen	Flow
0	0	0	0	3834
4	1	1	1	4161
7	1	1	1	4195

Disaster Scenario 2				
Line	Load	Bus	Gen	Flow
0	0	0	0	4279
4	0	0	0	4292
6	0	0	0	4292

Disaster Scenario 3				
Line	Load	Bus	Gen	Flow
0	0	0	0	3205
4	1	1	1	3556
0	3	3	3	4217

Lower Bound: **3773**

Upper Bound: **4235** (Clairvoyant)

Configuration Generation: Example

Storage Capacity: **10**

Disaster Scenario 1				
Line	Load	Bus	Gen	Flow
0	0	0	0	3834
4	1	1	1	4161
7	1	1	1	4195

Disaster Scenario 2				
Line	Load	Bus	Gen	Flow
0	0	0	0	4279
4	0	0	0	4292
6	0	0	0	4292

Disaster Scenario 3				
Line	Load	Bus	Gen	Flow
0	0	0	0	3205
4	1	1	1	3556
0	3	3	3	4217

Range: **3773** - **4235**

Configuration Generation: Example

Storage Capacity: **10**

Disaster Scenario 1				
Line	Load	Bus	Gen	Flow
0	0	0	0	3834
4	1	1	1	4161
7	1	1	1	4195

Disaster Scenario 2				
Line	Load	Bus	Gen	Flow
0	0	0	0	4279
4	0	0	0	4292
6	0	0	0	4292

Disaster Scenario 3				
Line	Load	Bus	Gen	Flow
0	0	0	0	3205
4	1	1	1	3556
0	3	3	3	4217

Storage Consensus: **[0,3,3,3]** Flow: **4110**

Range: **3773** - **4235**

Configuration Generation: Example

Storage Capacity: **10**

Disaster Scenario 1				
Line	Load	Bus	Gen	Flow
0	0	0	0	3834
4	1	1	1	4161
7	1	1	1	4195

Disaster Scenario 2				
Line	Load	Bus	Gen	Flow
0	0	0	0	4279
4	0	0	0	4292
6	0	0	0	4292

Disaster Scenario 3				
Line	Load	Bus	Gen	Flow
0	0	0	0	3205
4	1	1	1	3556
0	3	3	3	4217

Configuration Generation: Example

Storage Capacity: **10**

Disaster Scenario 1				
Line	Load	Bus	Gen	Flow
0	0	0	0	3834
4	1	1	1	4161
7	1	1	1	4195
0	1	1	1	4049

Disaster Scenario 2				
Line	Load	Bus	Gen	Flow
0	0	0	0	4279
4	0	0	0	4292
6	0	0	0	4292

Disaster Scenario 3				
Line	Load	Bus	Gen	Flow
0	0	0	0	3205
4	1	1	1	3556
0	3	3	3	4217

Configuration Generation: Example

Storage Capacity: **10**

Disaster Scenario 1				
Line	Load	Bus	Gen	Flow
0	0	0	0	3834
4	1	1	1	4161
7	1	1	1	4195
0	1	1	1	4049

Disaster Scenario 2				
Line	Load	Bus	Gen	Flow
0	0	0	0	4279
4	0	0	0	4292
6	0	0	0	4292

Disaster Scenario 3				
Line	Load	Bus	Gen	Flow
0	0	0	0	3205
4	1	1	1	3556
0	3	3	3	4217
4	0	0	0	3210

Configuration Generation: Example

Storage Capacity: **10**

Disaster Scenario 1				
Line	Load	Bus	Gen	Flow
0	0	0	0	3834
4	1	1	1	4161
7	1	1	1	4195
0	1	1	1	4049
4	0	0	0	3937

Disaster Scenario 2				
Line	Load	Bus	Gen	Flow
0	0	0	0	4279
4	0	0	0	4292
6	0	0	0	4292

Disaster Scenario 3				
Line	Load	Bus	Gen	Flow
0	0	0	0	3205
4	1	1	1	3556
0	3	3	3	4217
4	0	0	0	3210

Configuration Generation: Example

Storage Capacity: **10**

Disaster Scenario 1				
Line	Load	Bus	Gen	Flow
0	0	0	0	3834
4	1	1	1	4161
7	1	1	1	4195
0	1	1	1	4049
4	0	0	0	3937

Disaster Scenario 2				
Line	Load	Bus	Gen	Flow
0	0	0	0	4279
4	0	0	0	4292
6	0	0	0	4292

Disaster Scenario 3				
Line	Load	Bus	Gen	Flow
0	0	0	0	3205
4	1	1	1	3556
0	3	3	3	4217
4	0	0	0	3210
6	1	1	1	3559

Configuration Generation: Example

Storage Capacity: **10**

Disaster Scenario 1				
Line	Load	Bus	Gen	Flow
0	0	0	0	3834
4	1	1	1	4161
7	1	1	1	4195
0	1	1	1	4049
4	0	0	0	3937
1	1	1	1	4102

Disaster Scenario 2				
Line	Load	Bus	Gen	Flow
0	0	0	0	4279
4	0	0	0	4292
6	0	0	0	4292

Disaster Scenario 3				
Line	Load	Bus	Gen	Flow
0	0	0	0	3205
4	1	1	1	3556
0	3	3	3	4217
4	0	0	0	3210
6	1	1	1	3559

Configuration Generation: Example

Storage Capacity: **10**

Disaster Scenario 1				
Line	Load	Bus	Gen	Flow
0	0	0	0	3834
4	1	1	1	4161
7	1	1	1	4195
0	1	1	1	4049
4	0	0	0	3937
1	1	1	1	4102

Disaster Scenario 2				
Line	Load	Bus	Gen	Flow
0	0	0	0	4279
4	0	0	0	4292
6	0	0	0	4292
2	0	0	0	4292
1	0	0	0	4287

Disaster Scenario 3				
Line	Load	Bus	Gen	Flow
0	0	0	0	3205
4	1	1	1	3556
0	3	3	3	4217
4	0	0	0	3210
6	1	1	1	3559

Configuration Generation: Example

Storage Capacity: **10**

Disaster Scenario 1				
Line	Load	Bus	Gen	Flow
0	0	0	0	3834
4	1	1	1	4161
7	1	1	1	4195
0	1	1	1	4049
4	0	0	0	3937
1	1	1	1	4102

Disaster Scenario 2				
Line	Load	Bus	Gen	Flow
0	0	0	0	4279
4	0	0	0	4292
6	0	0	0	4292
2	0	0	0	4292
1	0	0	0	4287

Disaster Scenario 3				
Line	Load	Bus	Gen	Flow
0	0	0	0	3205
4	1	1	1	3556
0	3	3	3	4217
4	0	0	0	3210
6	1	1	1	3559

Storage Consensus: **[1,3,3,3]** Flow: **4202**

Optimal Flow (MIP): **4202**

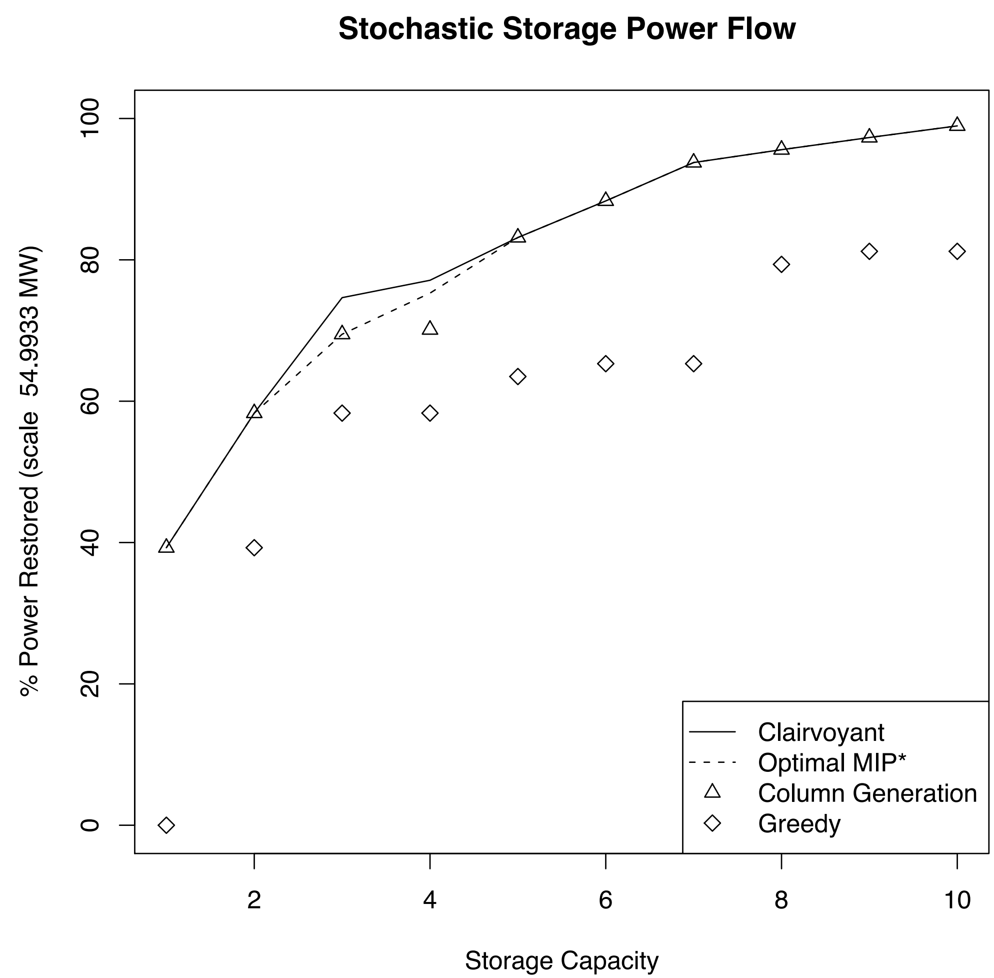
Stochastic Storage Benchmarks - Experiments

- Compare with a clairvoyant solution
  - If every scenario was independent, what is the best we could do.
- Compare with a greedy solution
  - If you store items based on the static properties of the network, how well would we do?

Legend

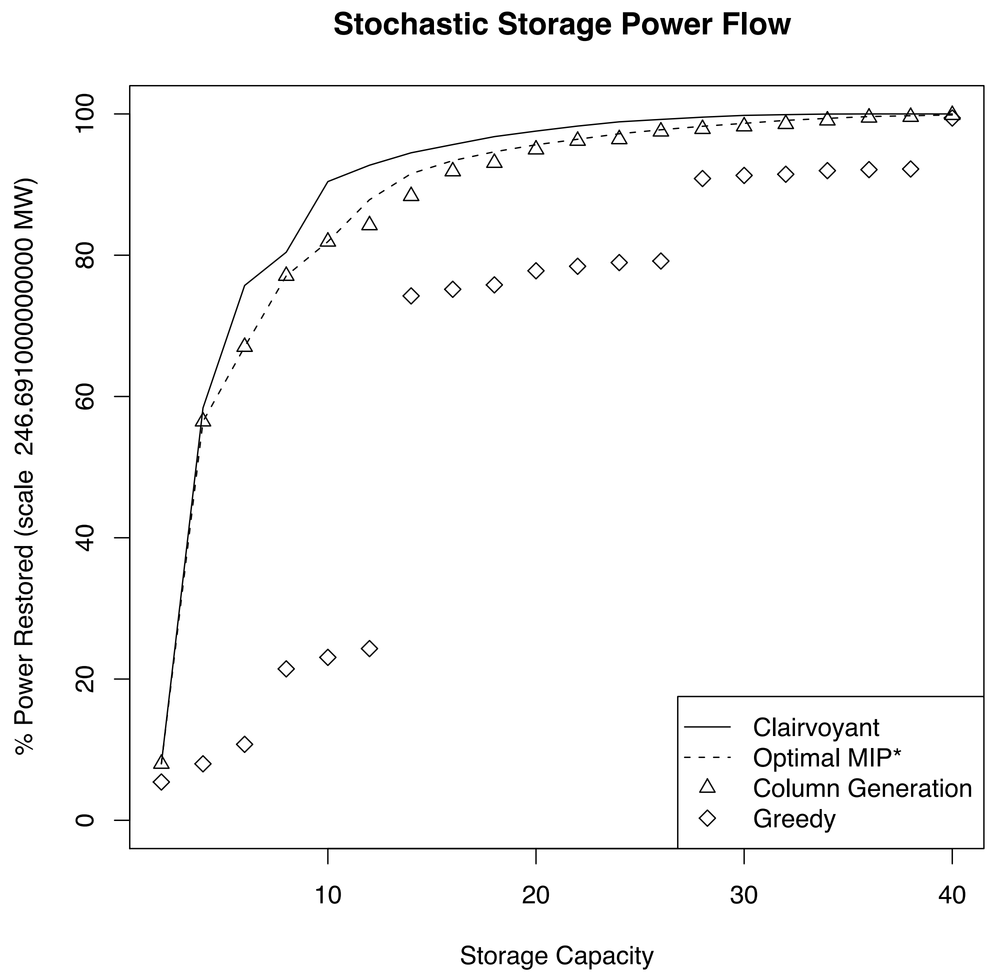
———	Clairvoyant
- - - - - - -	Optimal MIP*
△	Column Generation
◇	Greedy

Benchmark 1



Network Size: 326 Scenarios: 3 Max Damage: 22

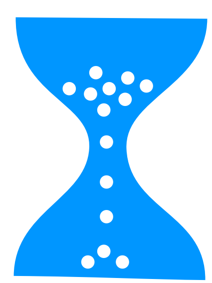
Benchmark 3

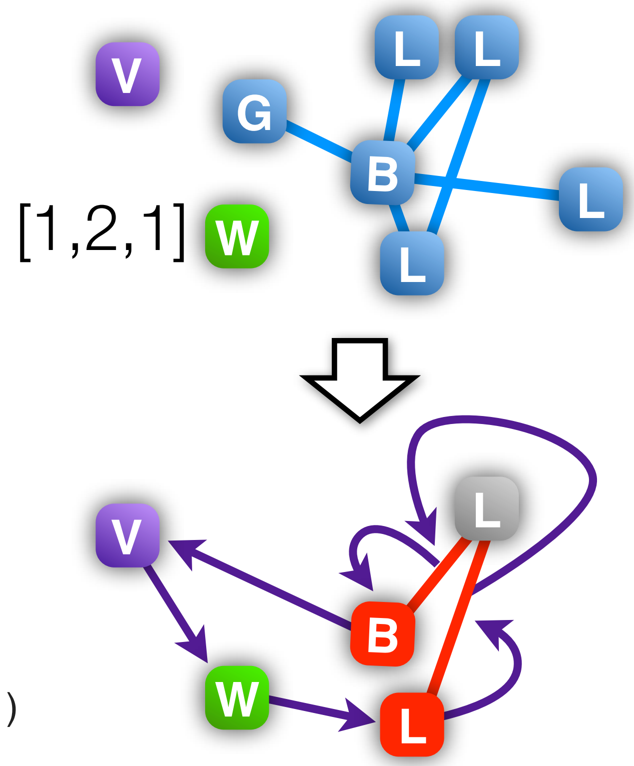


Network Size: 266 Scenarios: 18 Max Damage: 61

Restoration Routing Problem

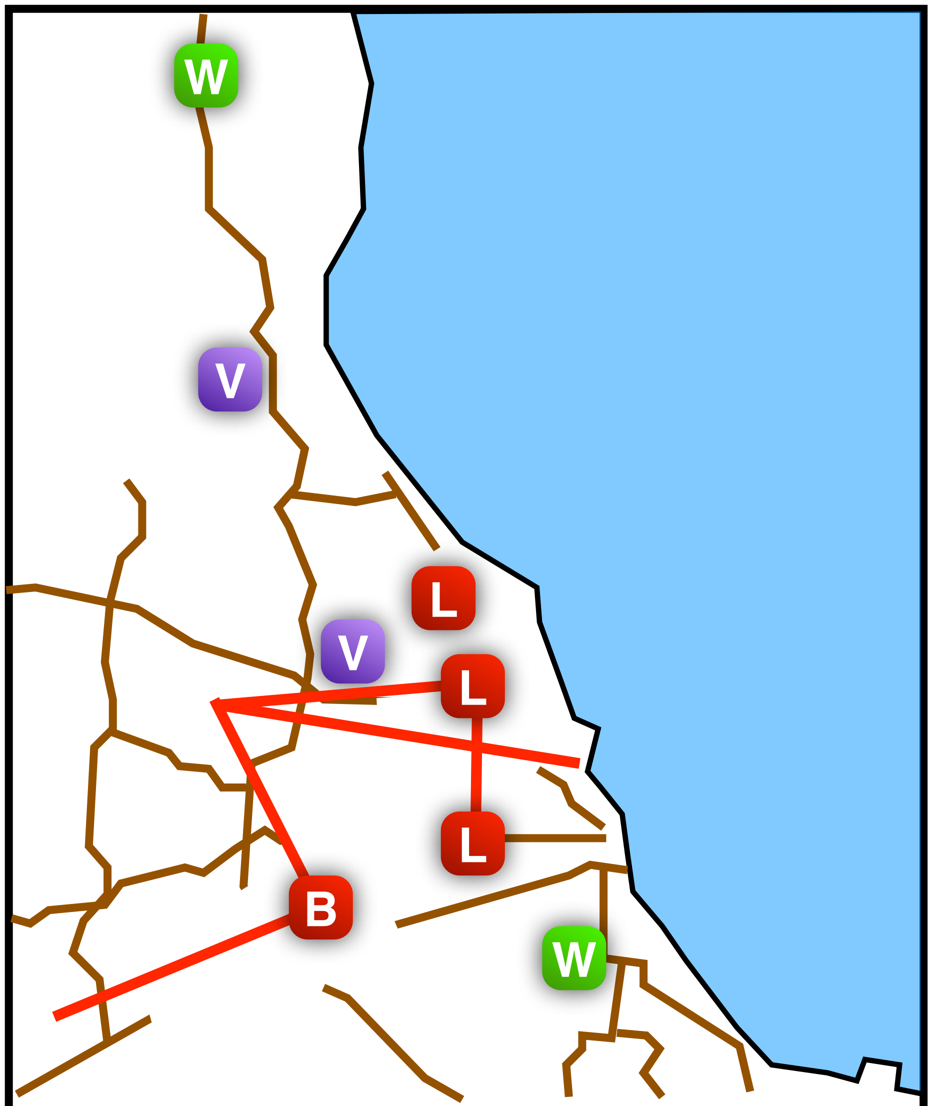
Disaster Specific
Power Restoration and
Routing Decisions





See: **Vehicle Routing for the Last Mile of Power System Restoration.** P. Van Hentenryck, C. Coffrin, and R. Bent. (PSCC'11)

Problem Formulation



- Use the available vehicles and warehouses to perform all of the repairs as fast as possible
- Classically called Pickup and Delivery Vehicle Routing Problem
- This is a well studied in the optimization community
- Output: Restoration Plan, the time each damaged item comes online

Issues...

1. Which do we prefer,

- Recovery teams use as little gas as possible?

- P

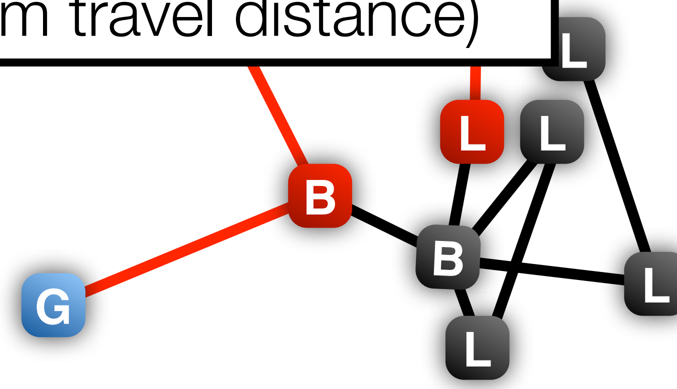
2. It is

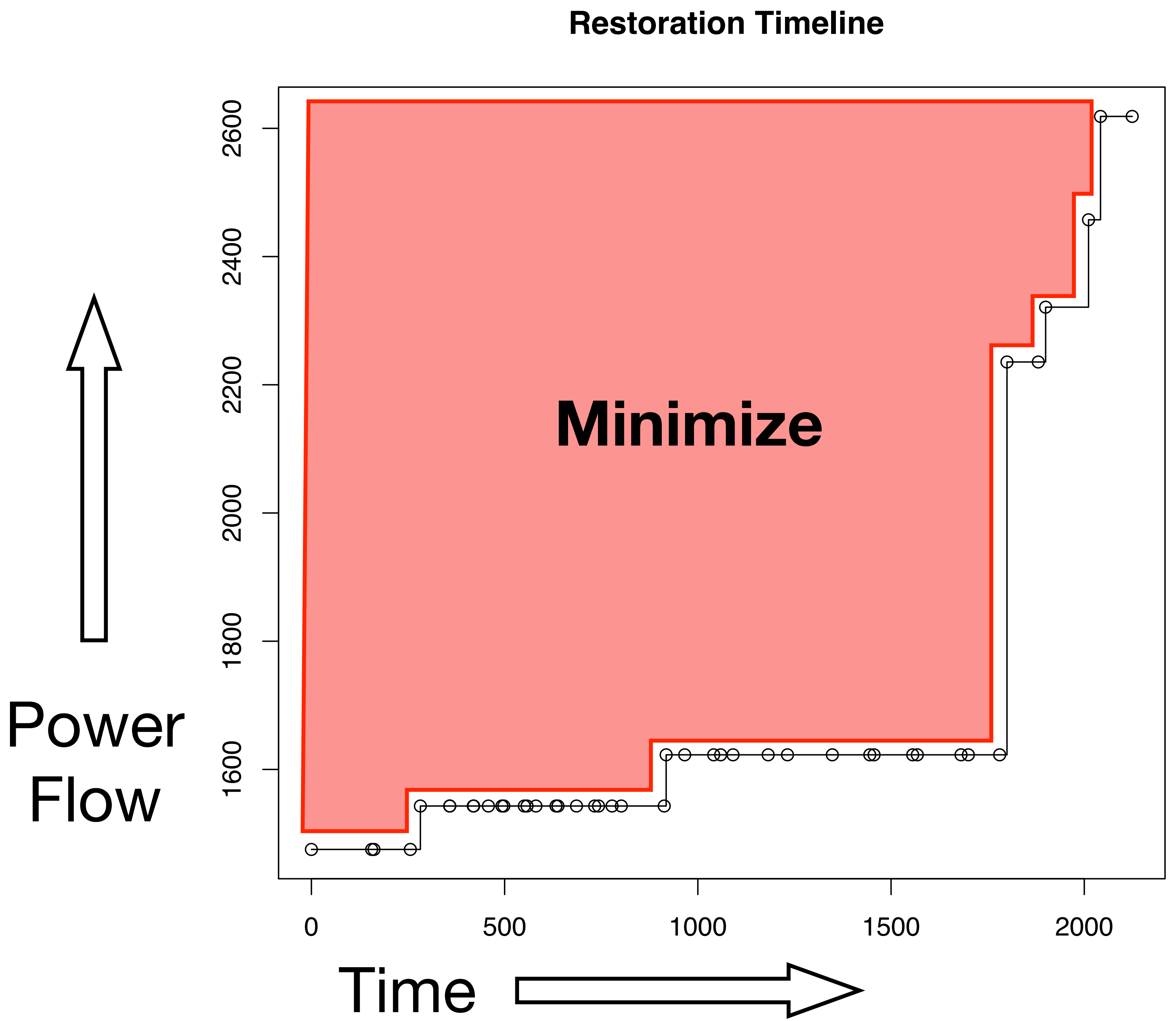
- C

Restoration Objective

Restore all power demands as soon as possible.

(VERY different than classic minimum travel distance)





Restoration Timeline
Minimize
2600
2400
2200
2000
1800
1600
0
500
1000
1500
2000
Power Flow
Time

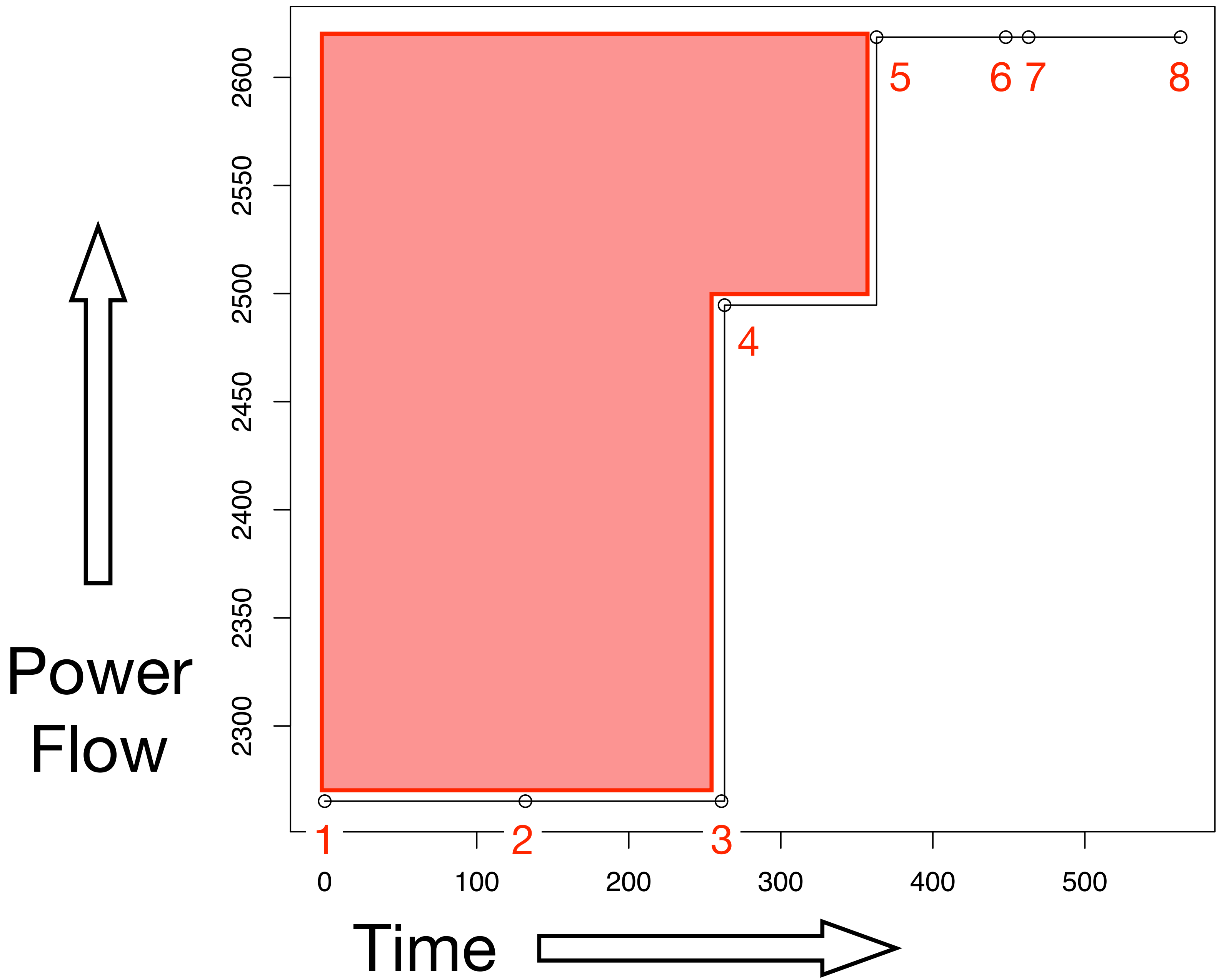
Restoration Objective Calculation

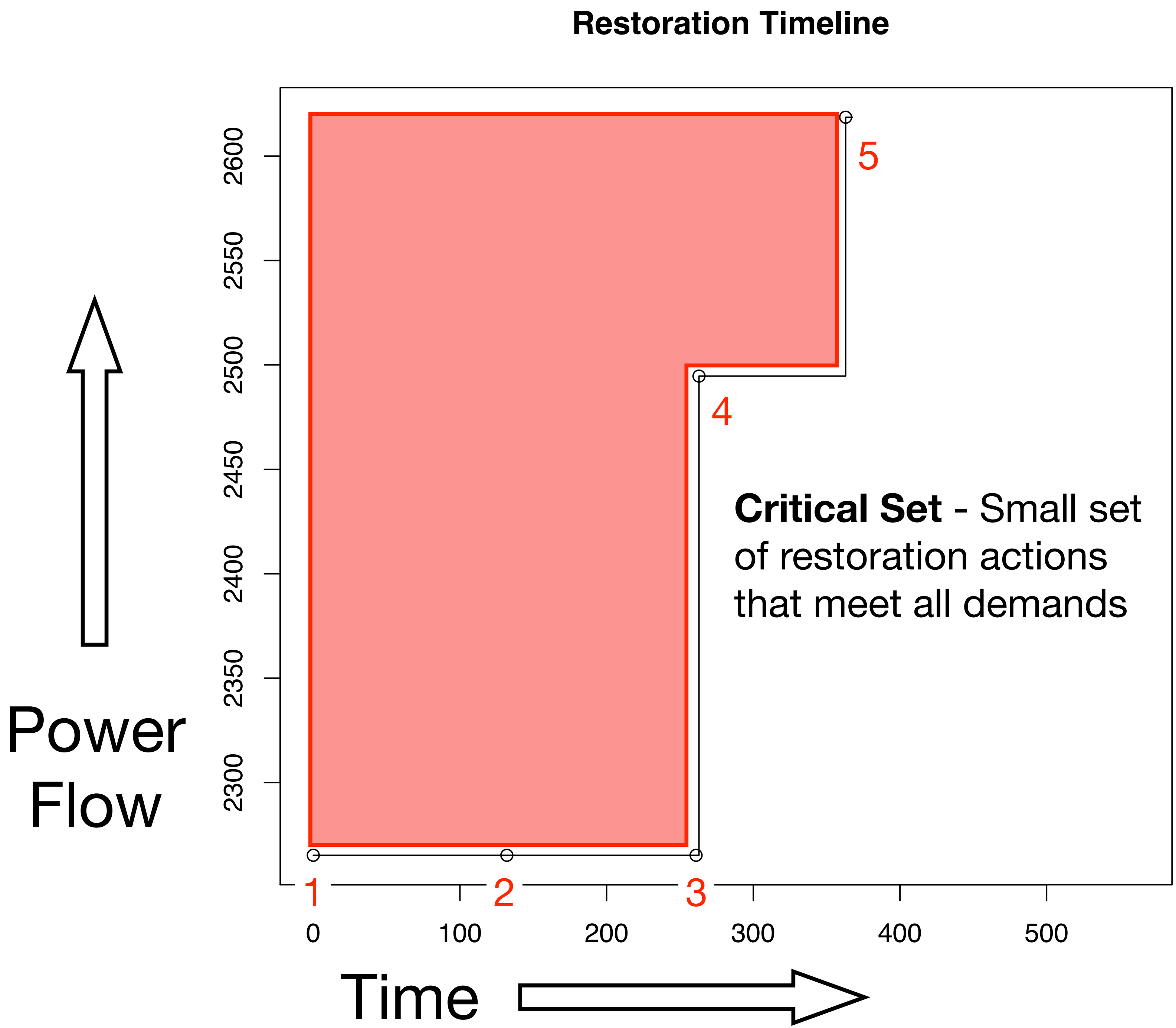
- Given,
  - A restoration plan (i.e. when is each item repaired)
  - A power-flow black-box
- We c

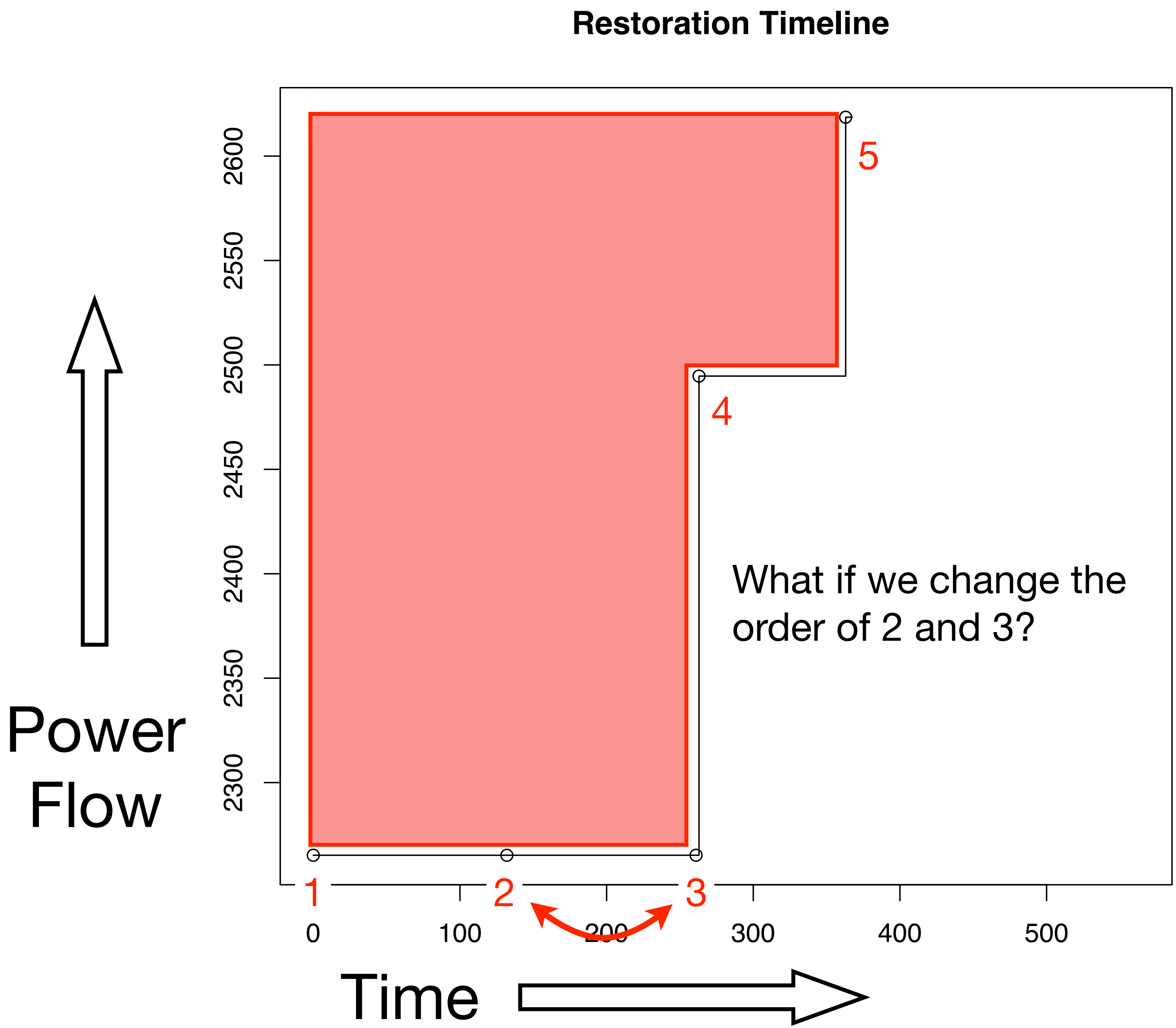
What about the **minimization** part?

$$\sum_i (\text{AllDemands} - \text{DemandsMet}(\mathcal{PN}, \mathcal{DS}(R_i)))(R_{i+1} - R_i)$$

Restoration Timeline




Restoration Timeline
2600
2550
2500
2450
2400
2350
2300
0
100
200
300
400
500
1
2
3
4
5
Critical Set - Small set of restoration actions that meet all demands
Power Flow
Time


Restoration Timeline
2600
2550
2500
2450
2400
2350
2300
0
100
200
300
400
500
1
2
3
4
5
What if we change the order of 2 and 3?
Power Flow
Time


Restoration Timeline
Power Flow
Time
2300
2350
2400
2450
2500
2550
2600
0
100
200
300
400
500
1
3
2
4
5
Order - of restoration determines how much power flows at a particular time
Restoration Order: 1 > 3 > 2 > 4 > 5

Restoration Routing Algorithm

- 3-Stage Power Restoration Algorithm

    1. **Critical Set** (MIP/LNS) - Minimize the set of restoration actions need to meet all demands

    2. **Restoration Ordering** (MIP/LNS) - Order of restoration items of Stage 1

    3. **Precedence Routing** (LNS) - Vehicle routing enforcing the order of Stage 2

- MIP models are fairly strait forward, LNS is more interesting

Challenges: Restoration Order Problem

#	Item	Rest
0	--	0%
1	B22	0%
2	D49	0%
3	D17	47%
4	L26	100%

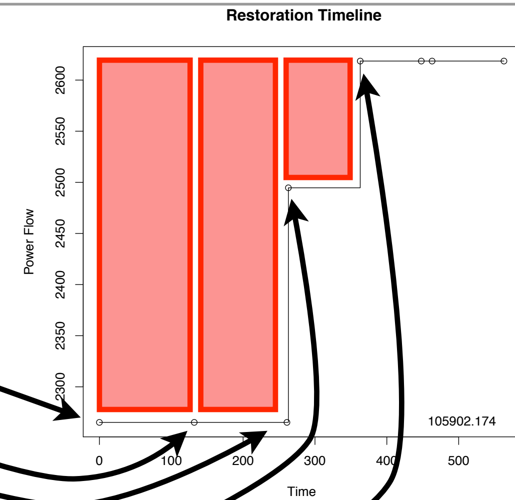
{}

{B22}

{B22,D49}

{B22,D49,D17}

{B22,D49,D17,L26}



- Just to evaluate this order the simulator must be called 4 times!

- Because of Braces's paradox we cannot make any assumptions about the flow of future restorations

Challenges: Restoration Order Problem

#	Item	Rest	
0	--	0%	{}
1	B22	0%	{B22}
2	D49	0%	{B22,D49}
3	D17	47%	{B22,D49,D17}
4	L26	100%	{B22,D49,D17,L26}

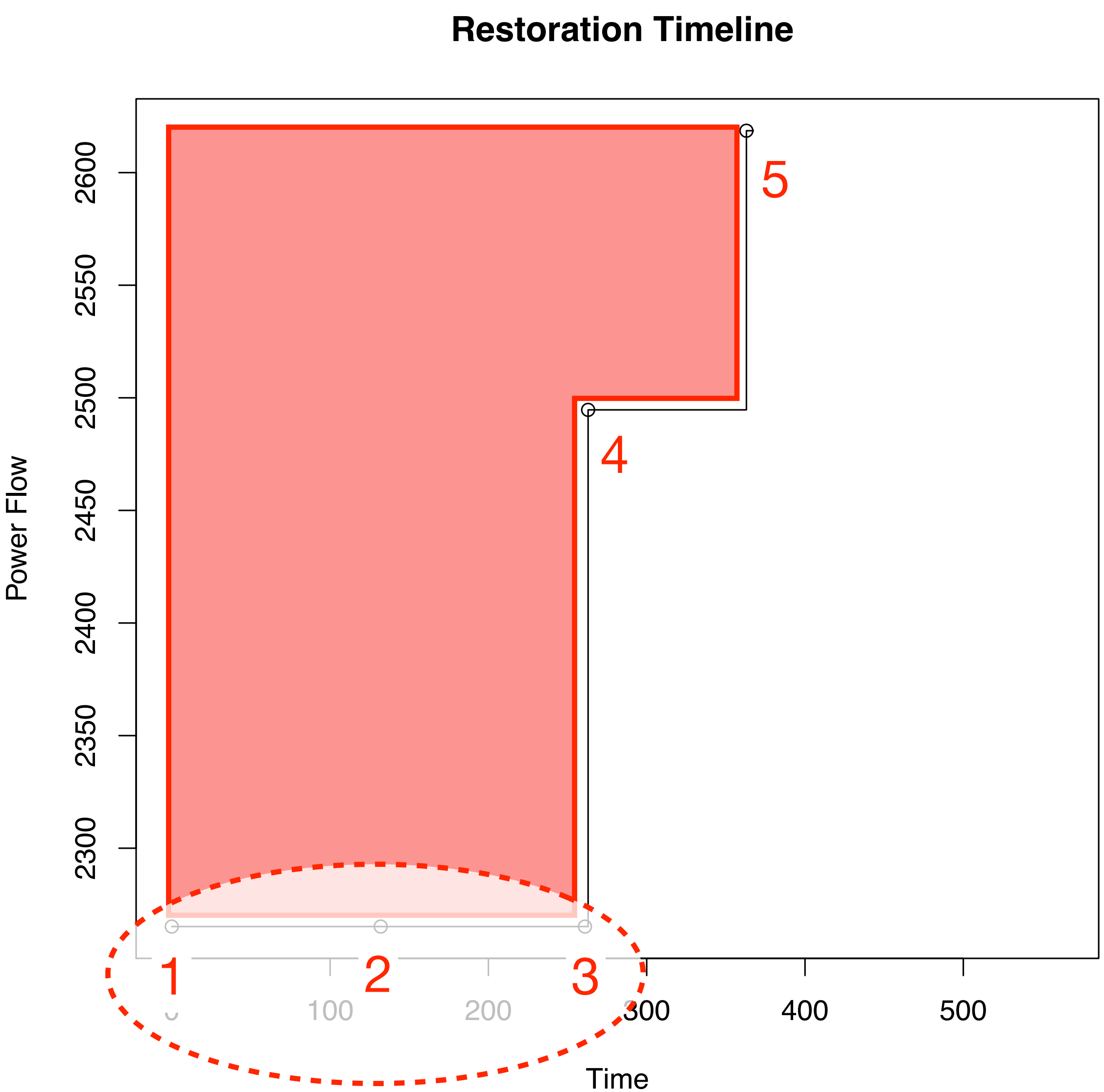
Restoration Order 1

#	Item	Rest	
0	--	0%	{}
1	D17	6%	{D17}
2	B22	34%	{D17,B22}
3	D49	47%	{D17,B22,D49}
4	L26	100%	{D17,B22,D49,L26}

Restoration Order 2

- Caching simulation flow values of restoration sets has potentially huge computational savings (but there an exponential number sets to cache...)
- This is particularly true for LS which only makes small changes to the solution
- Works quite well on our current benchmarks

Challenges: Precedence Routing Problem



Restoration Order: 1 > 2 > 3 > 4 > 5

Restoration Order - Increases vehicles travel time, in hopes of deceasing the blackout size.

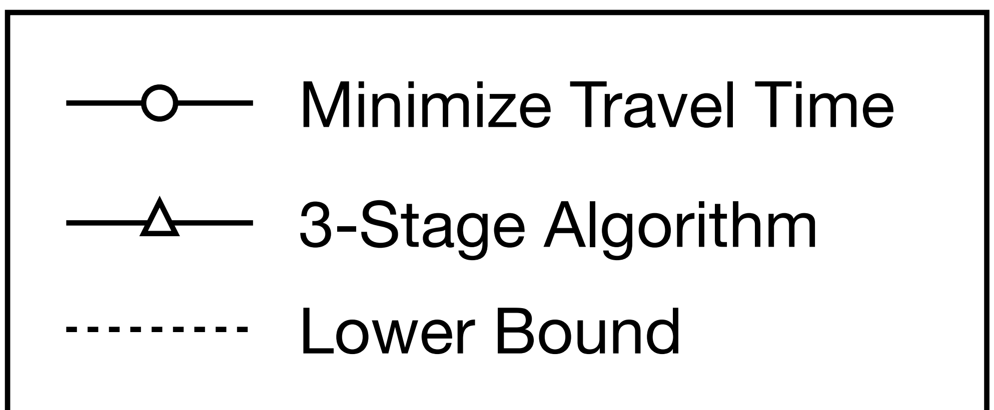
Restoration Order: {1,2,3} > 4 > 5

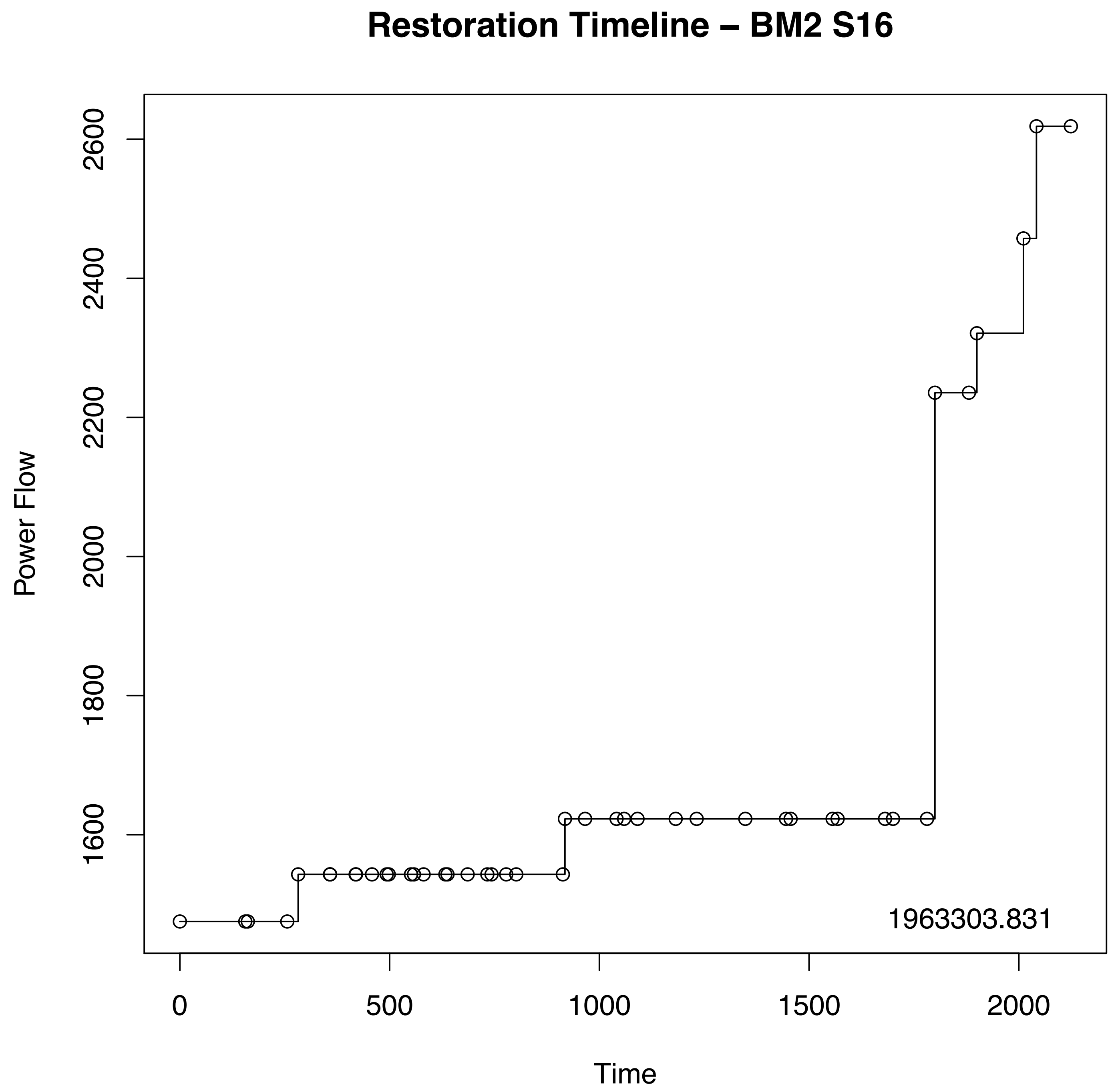
Restoration Routing Demo

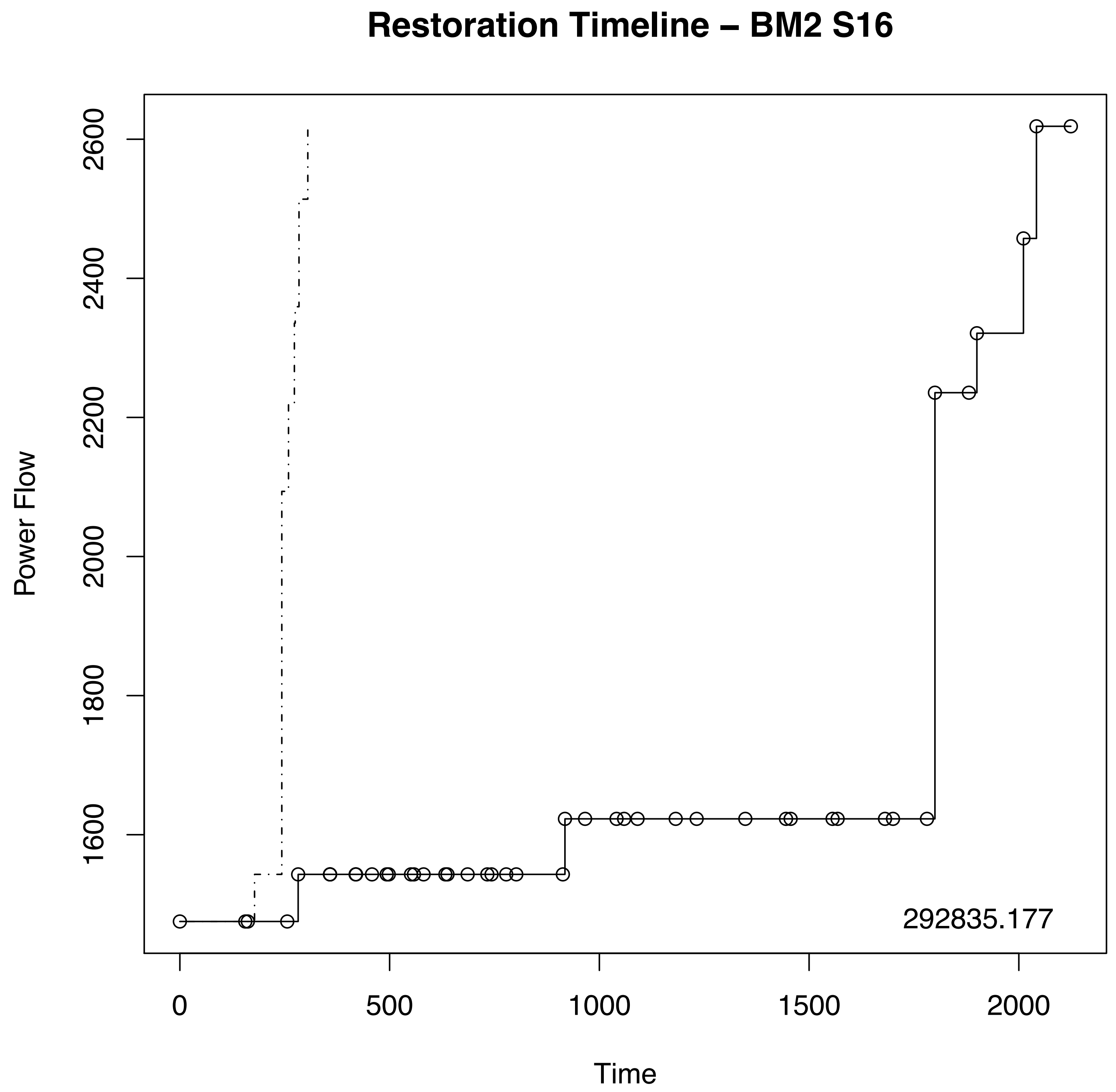
Restoration Routing - Benchmarks

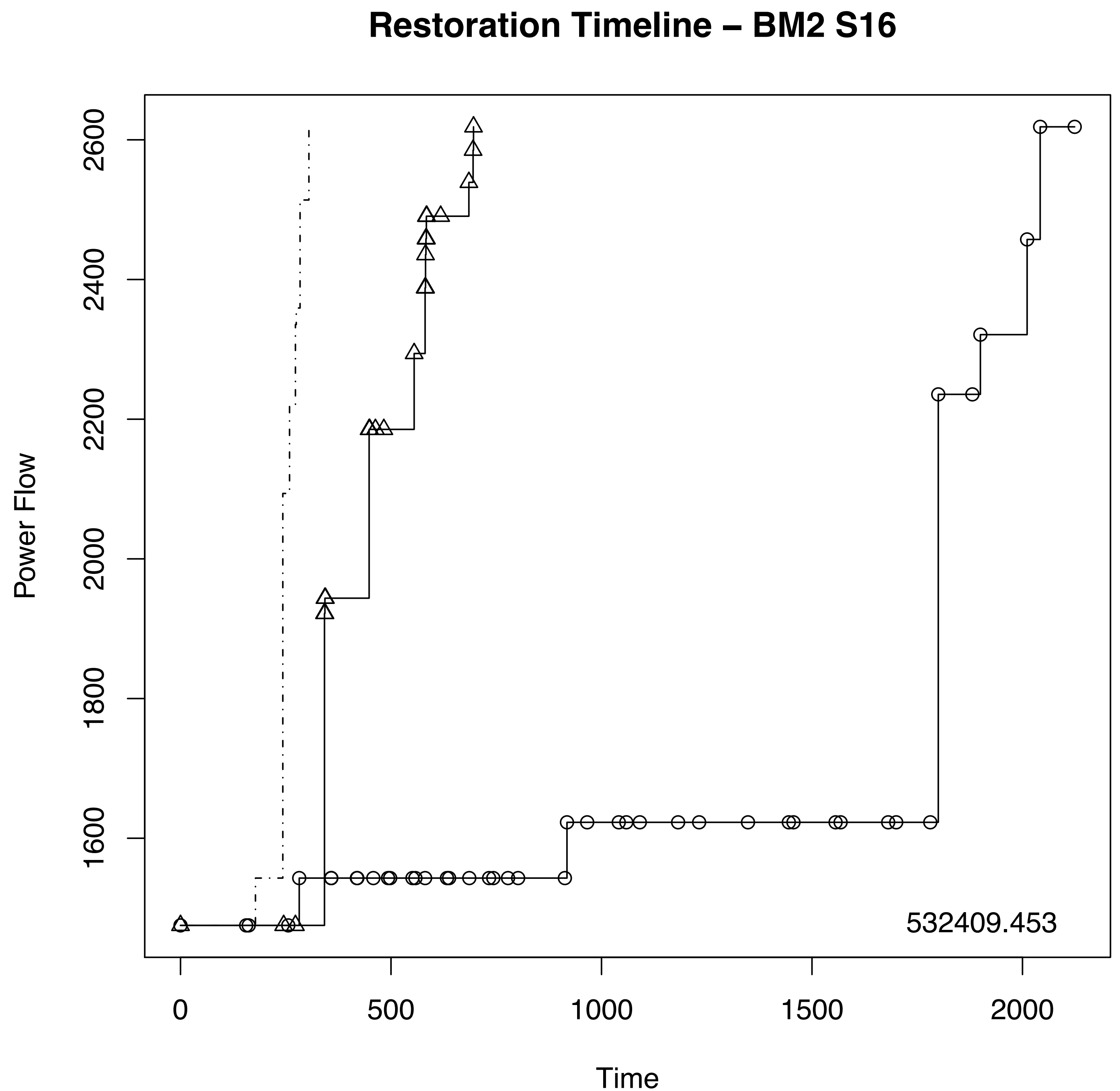
- 32 disaster scenarios on 3 power grids
  - Power grids and road networks based on United States infrastructure
  - Disasters generated with state-of-the-art disaster simulation tools (NHC)

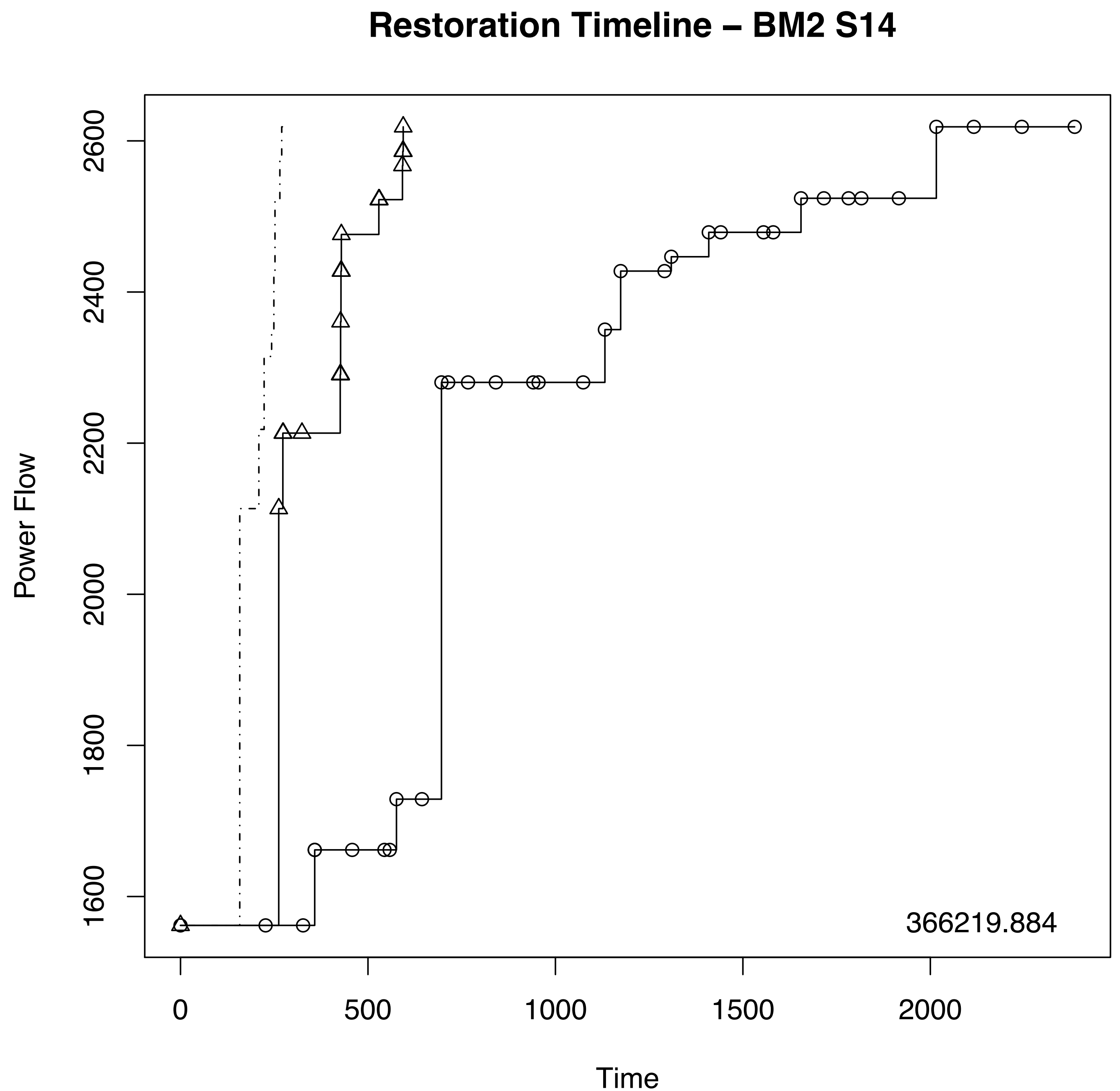
Legend

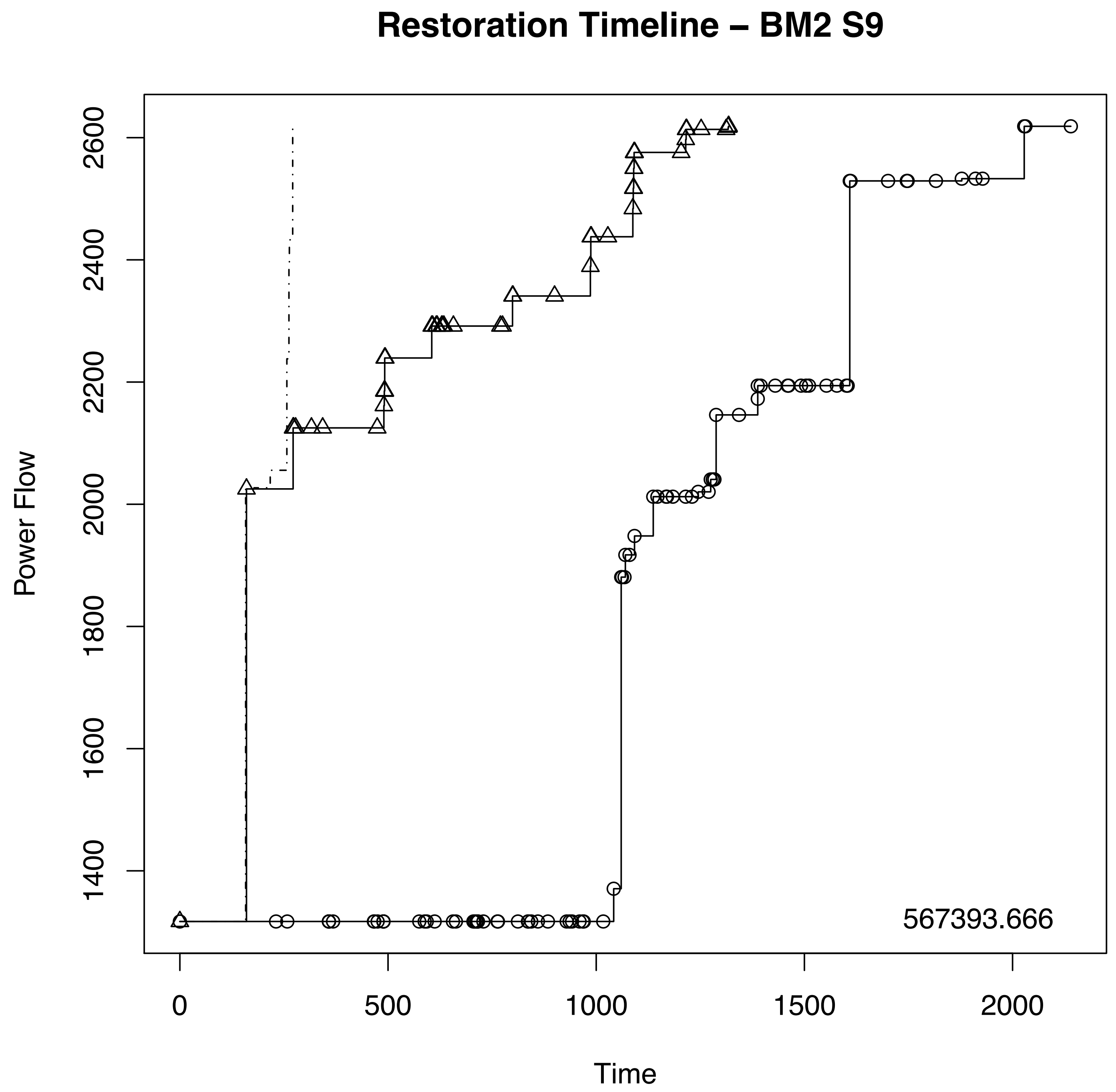


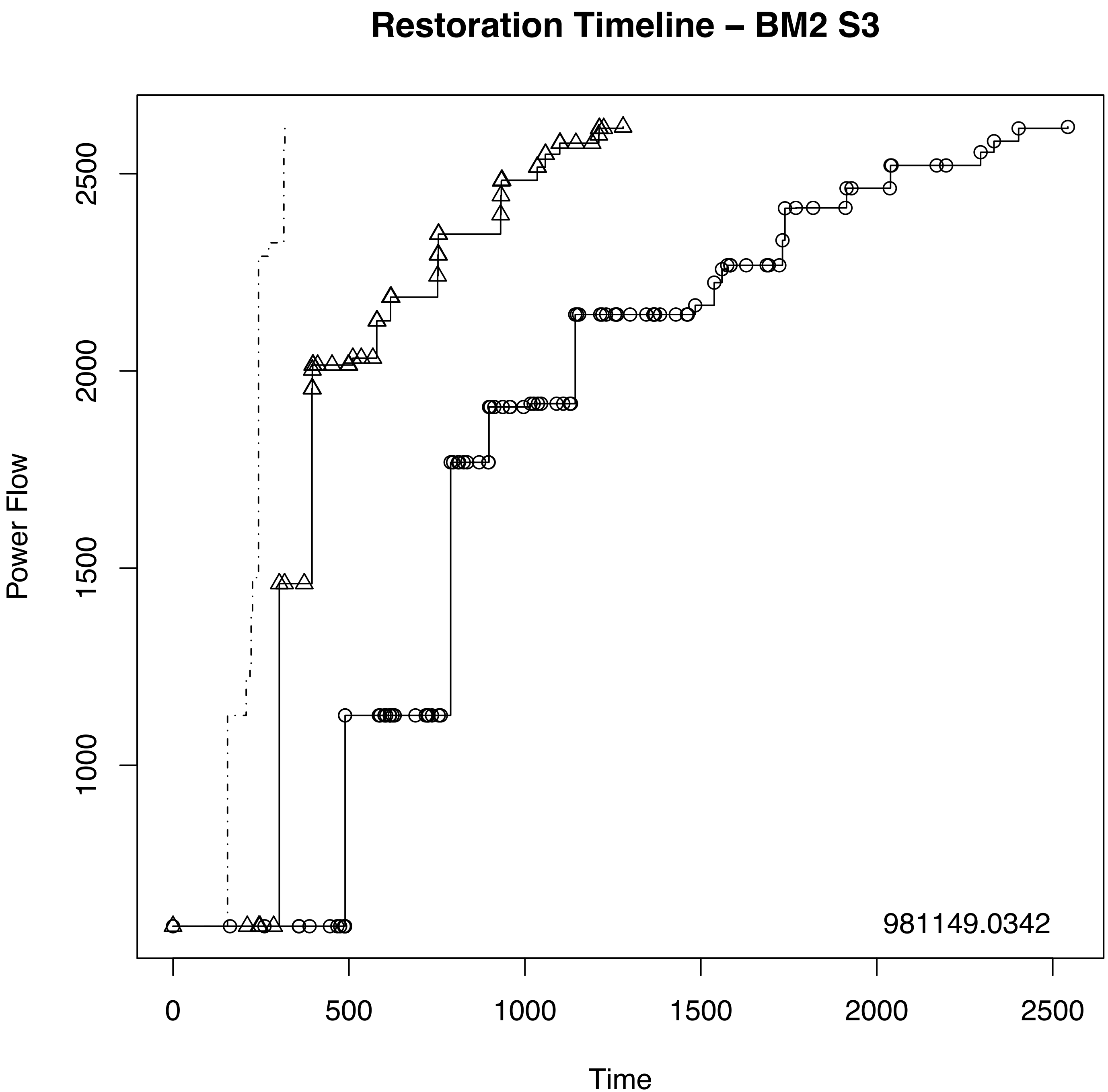

Restoration Timeline – BM2 S16
Power Flow
1600
1800
2000
2200
2400
2600
0
500
1000
1500
2000
Time
1963303.831


Restoration Timeline – BM2 S16
Power Flow
2600
2400
2200
2000
1800
1600
Time
0
500
1000
1500
2000
292835.177

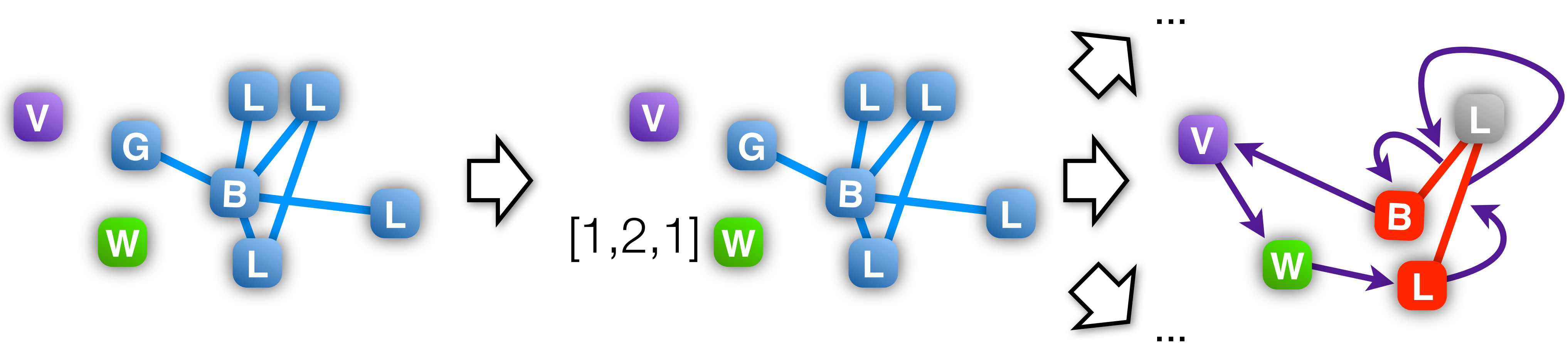

Restoration Timeline – BM2 S16
Power Flow
2600
2400
2200
2000
1800
1600
0
500
1000
1500
2000
Time
532409.453


Restoration Timeline – BM2 S14
Power Flow
1600
1800
2000
2200
2400
2600
0
500
1000
1500
2000
Time
366219.884


Restoration Timeline – BM2 S9
Power Flow
1400
1600
1800
2000
2200
2400
2600
Time
0
500
1000
1500
2000
567393.666

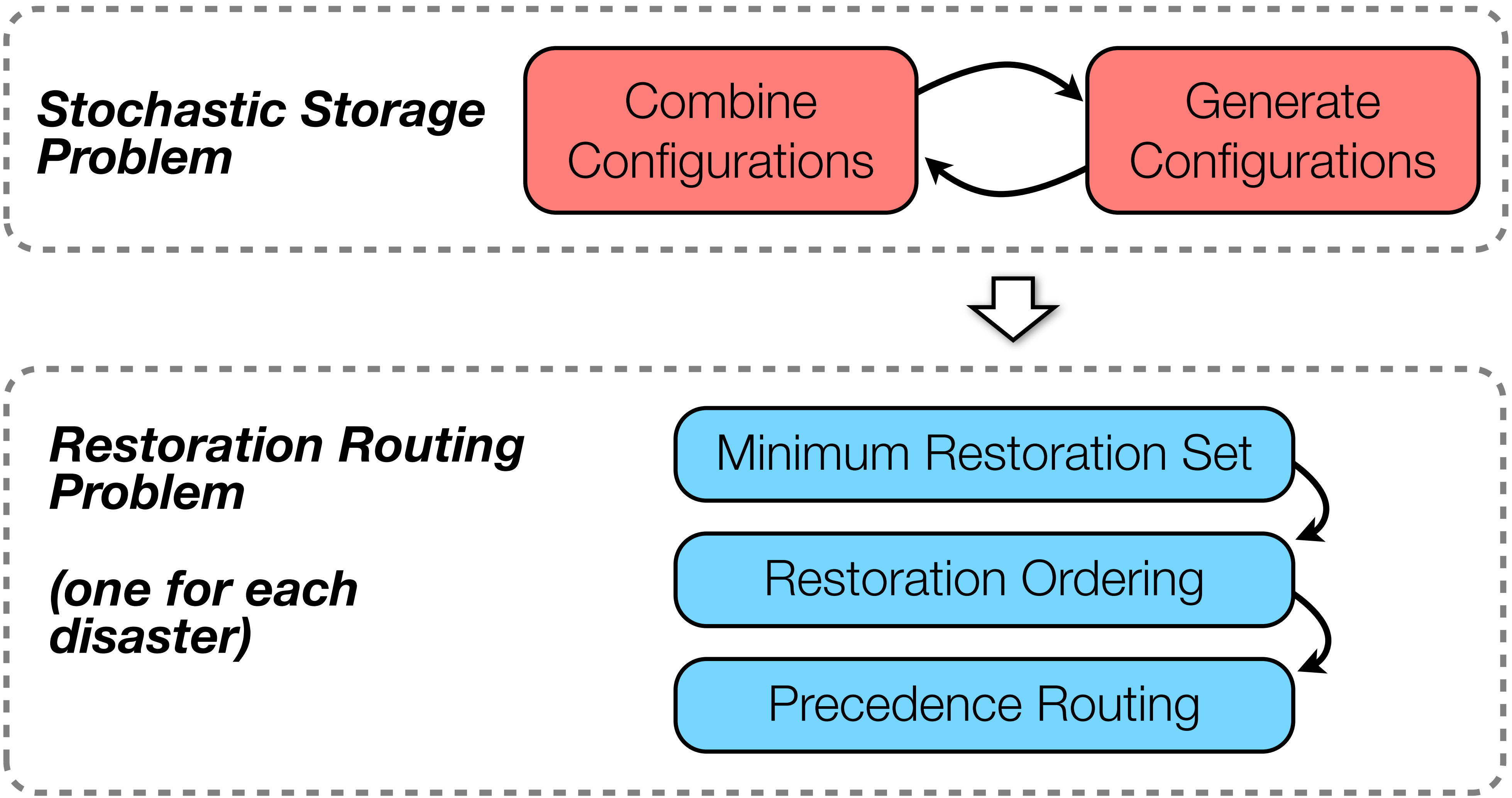

Restoration Timeline – BM2 S3
Power Flow
1000
1500
2000
2500
0
500
1000
1500
2000
2500
Time
981149.0342

Putting Them Together



See: **Strategic Planning for Power System Restoration.**
C. Coffrin, P. van Hentenryck, and R. Bent. (ICVRAM 2011)

Complete Algorithm



Power Restoration - Benchmarks

	Warehouses	Vehicles	Scenarios	PN Size
BM1	8	13	3	326
BM3	8	13	18	266
BM4	8	13	18	326

	BM1	BM3	BM4
Baseline	192866	606090	668064
PSRPP	141919	328673	355695
Improvement	**26.4%**	**45.8%**	**46.8%**

[Preliminary Results]

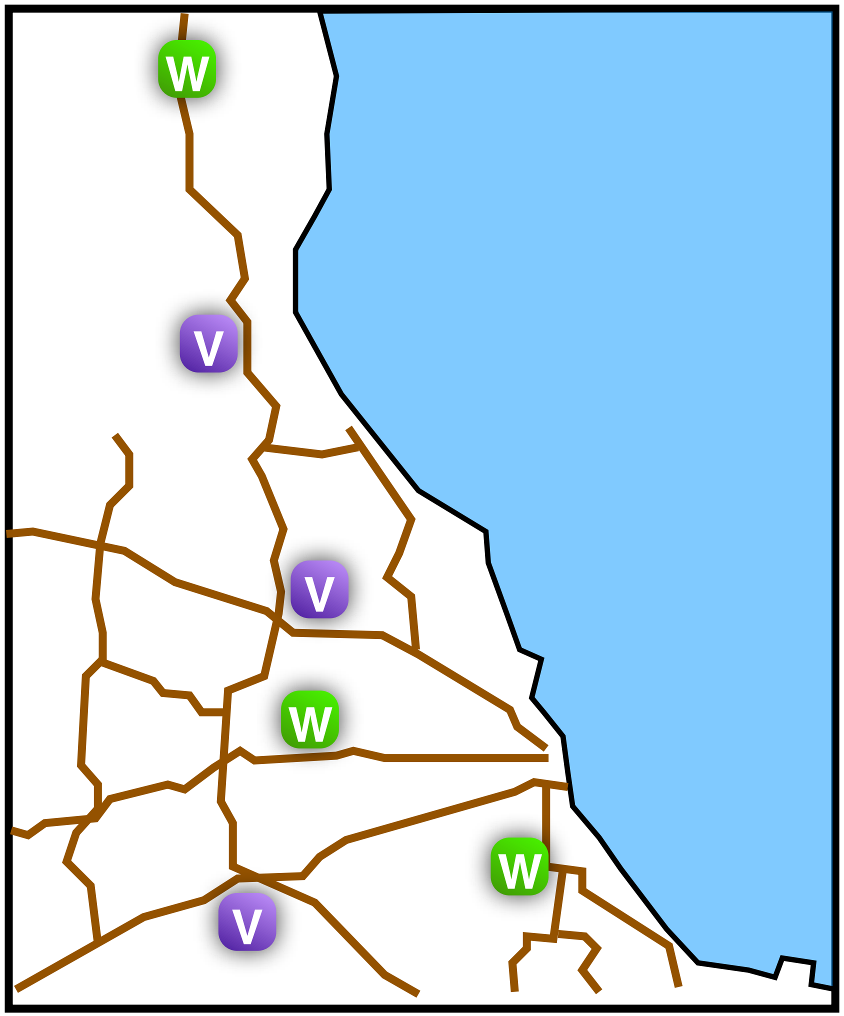
Contributions Summary

- Developed a multi-stage hybrid-optimization algorithm that meets NISAC's fast-response analysis and decision support requirements.
- Validated the algorithm's quality using lower bounds (relaxations).
- Developed several local search techniques for scaling the algorithm.
- Validated the local search's quality using globally optimal MIP models.
- Developed several heuristics which approximate current best practices.

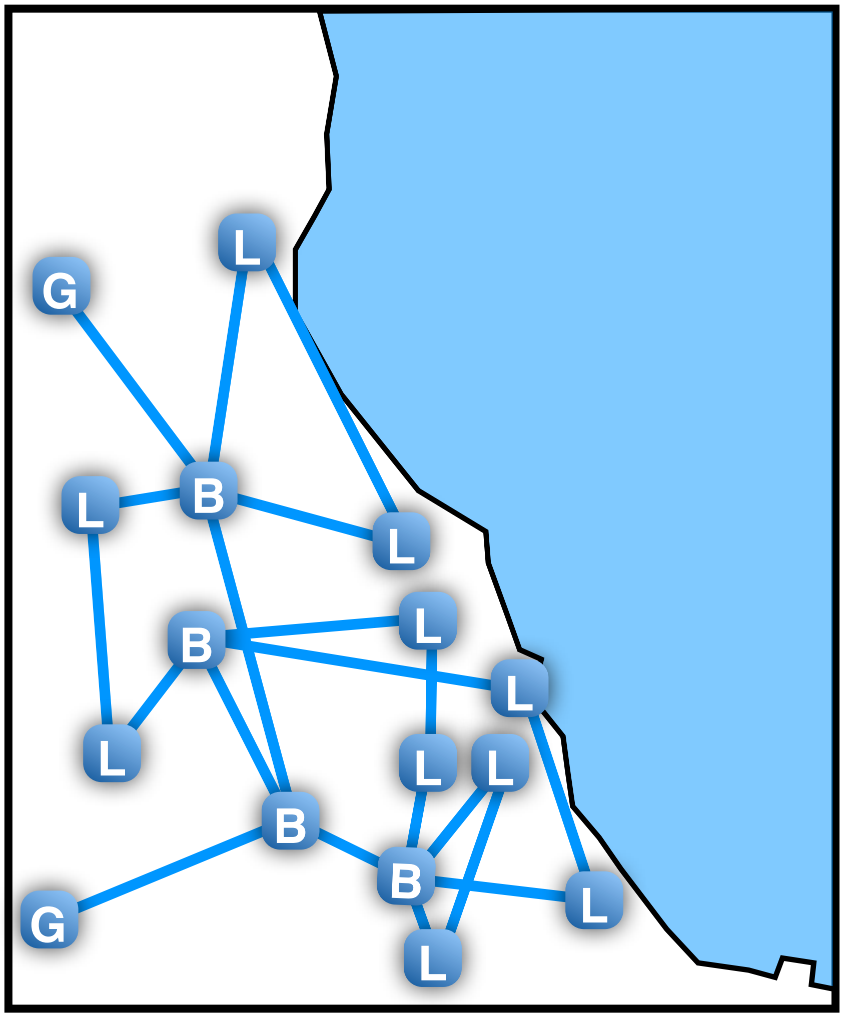
What’s Next?

Current Infrastructure

Infrastructure Systems



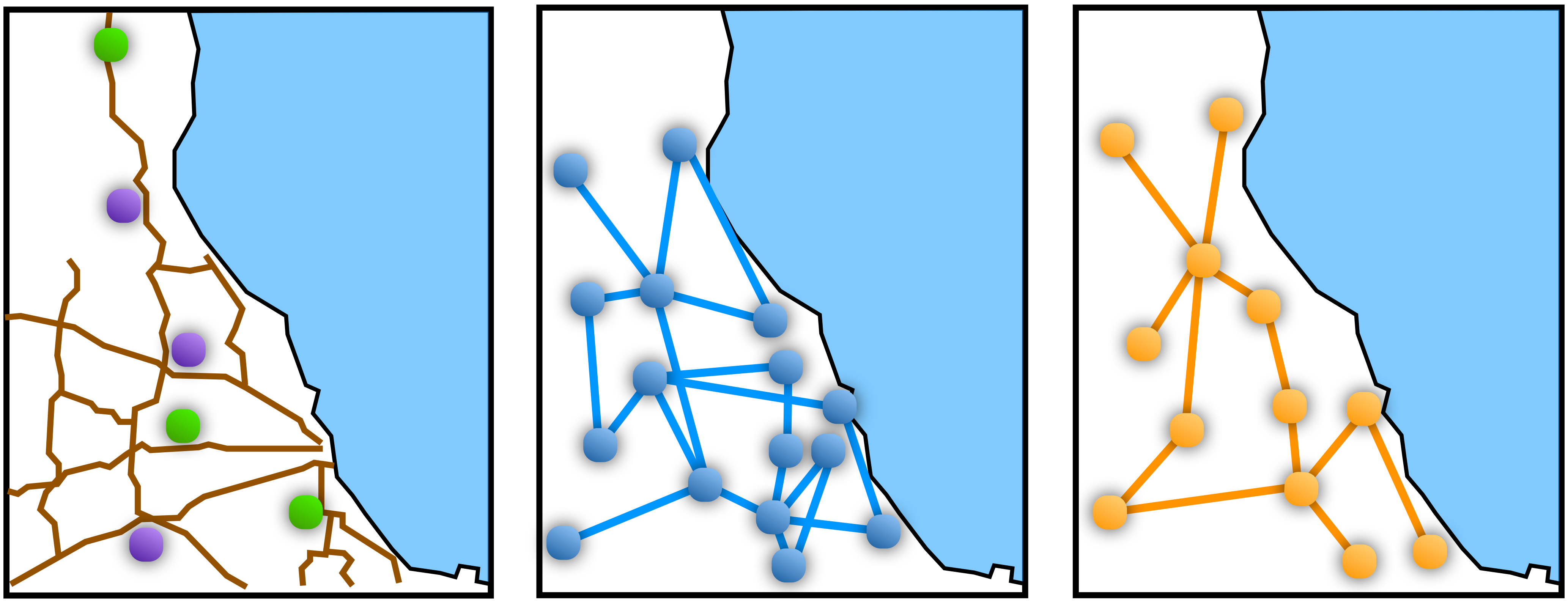
Transportation and Storage



Power System

Interdependent Infrastructure

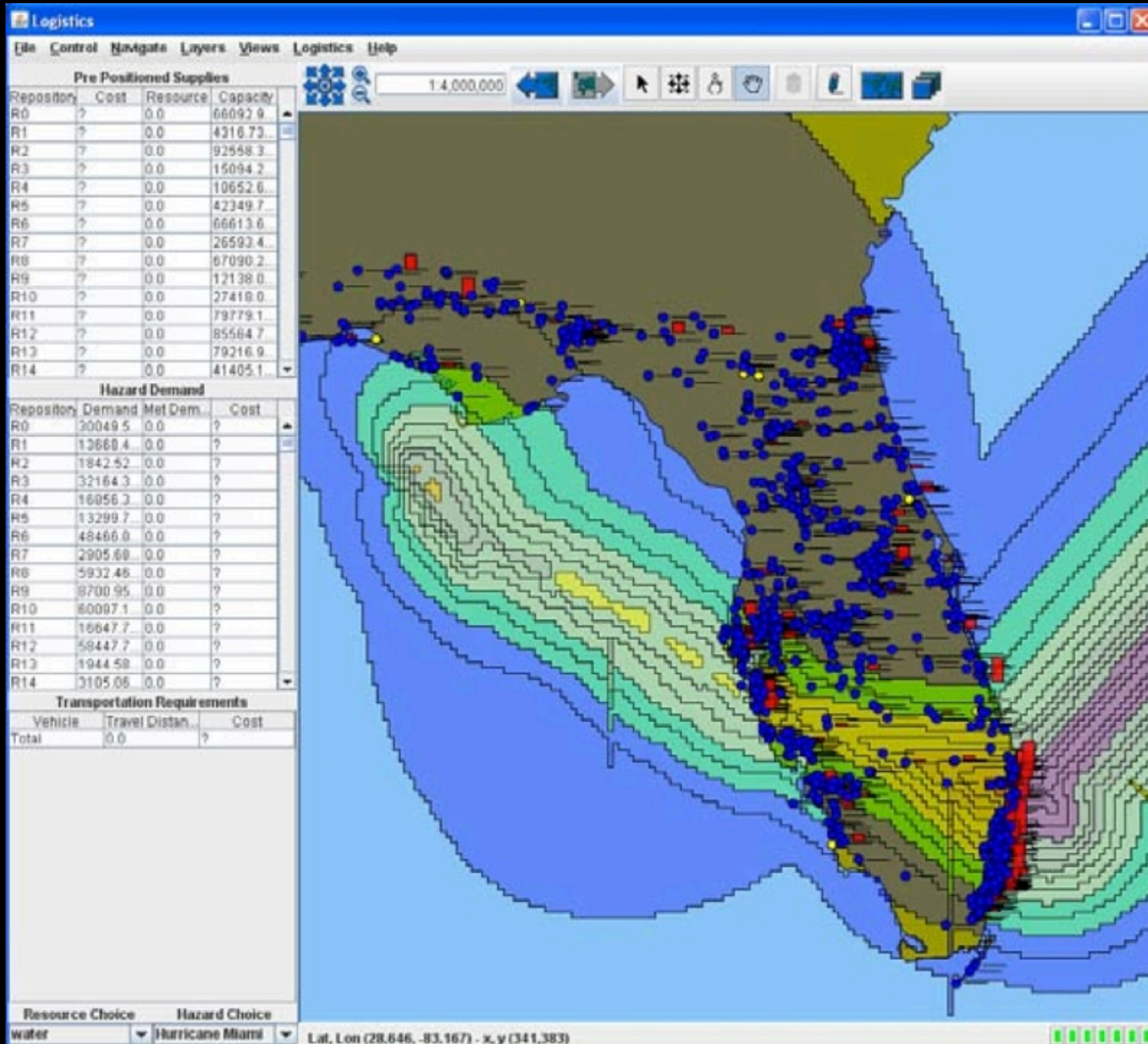
Infrastructure Systems



Transportation and Storage

Power System

Natural Gas System


Logistics
File Control Navigate Layers Views Logistics Help
1:4,000,000
Pre Positioned Supplies
Repository Cost Resource Capacity
R0 ? 0.0 66092.9...
R1 ? 0.0 4316.73...
R2 ? 0.0 92558.3...
R3 ? 0.0 15094.2...
R4 ? 0.0 10652.6...
R5 ? 0.0 42349.7...
R6 ? 0.0 66613.6...
R7 ? 0.0 26593.4...
R8 ? 0.0 67090.2...
R9 ? 0.0 12138.0...
R10 ? 0.0 27418.0...
R11 ? 0.0 79779.1...
R12 ? 0.0 85564.7...
R13 ? 0.0 79216.9...
R14 ? 0.0 41405.1...
Hazard Demand
Repository Demand Met Dem... Cost
R0 30049.5... 0.0 ?
R1 13660.4... 0.0 ?
R2 1842.52... 0.0 ?
R3 32164.3... 0.0 ?
R4 16856.3... 0.0 ?
R5 13299.7... 0.0 ?
R6 48466.0... 0.0 ?
R7 2905.69... 0.0 ?
R8 5932.46... 0.0 ?
R9 8700.95... 0.0 ?
R10 60097.1... 0.0 ?
R11 16647.7... 0.0 ?
R12 58447.7... 0.0 ?
R13 1944.58... 0.0 ?
R14 3105.06... 0.0 ?
Transportation Requirements
Vehicle Travel Distan... Cost
Total 0.0 ?
Resource Choice
Hazard Choice
water
Hurricane Miami
Lat, Lon (28.646, -83.167) - x, y (341,383)

Questions?