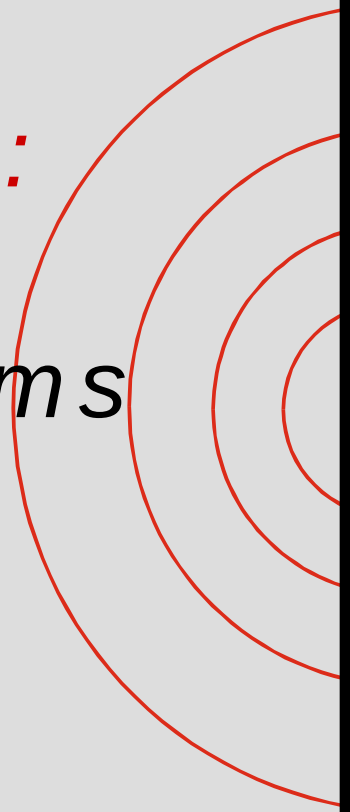
Rapidity and the Electric Power System: Earthquakes, Hurricanes, and Ice storms



The Four Fundamental Properties of Resilience

robustness

redundancy

resourcefulness

rapidity

Rapidity

Outline

- **Earthquake restoration**
  - Discrete event simulation
  - Optimization
- **Hurricane and ice storm restoration**
  - Statistics / survival analysis
  - Data envelopment analysis
- **Extensions to post-earthquake fires**

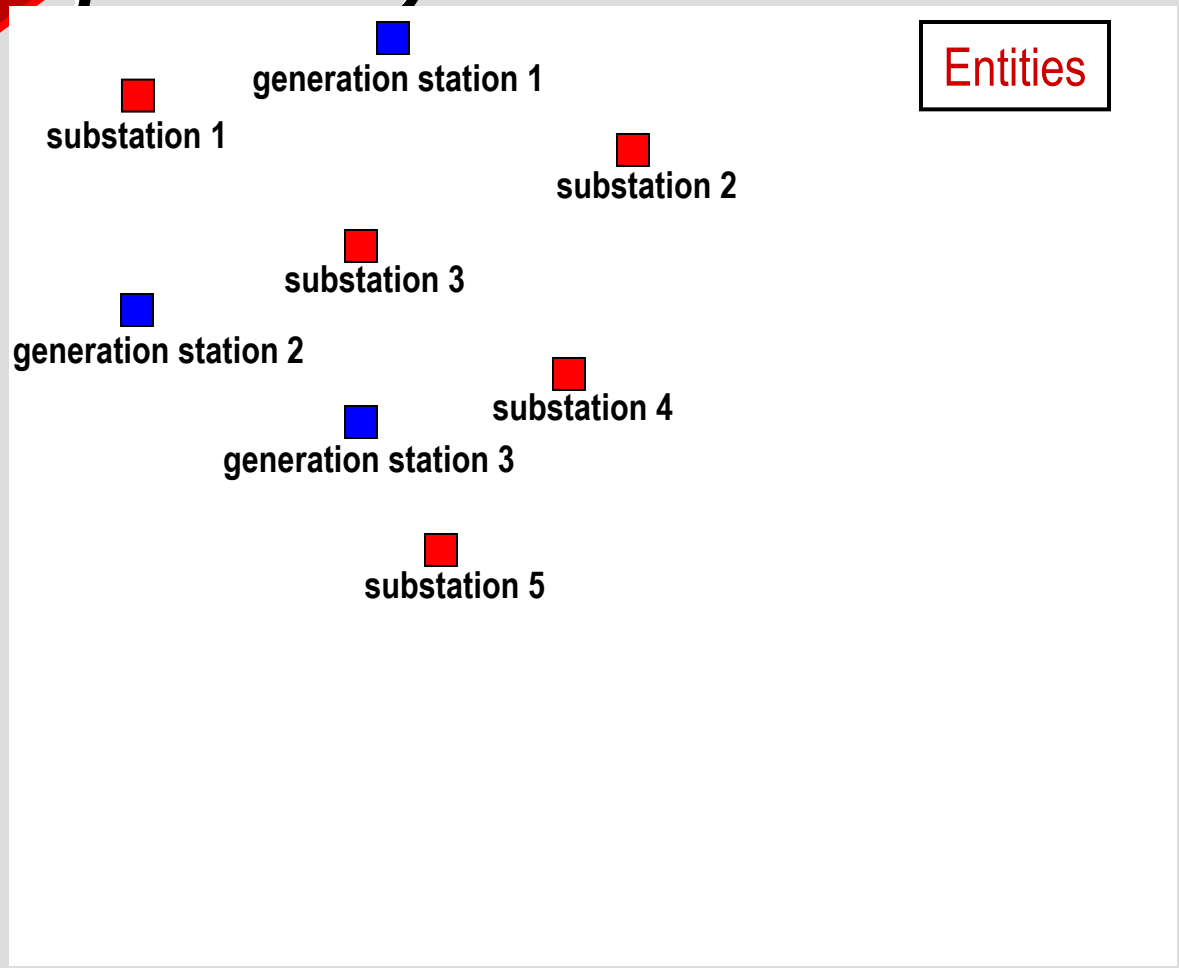
Northridge, CA

‘98 Ice Storm in Quebec

Hurricane Floyd

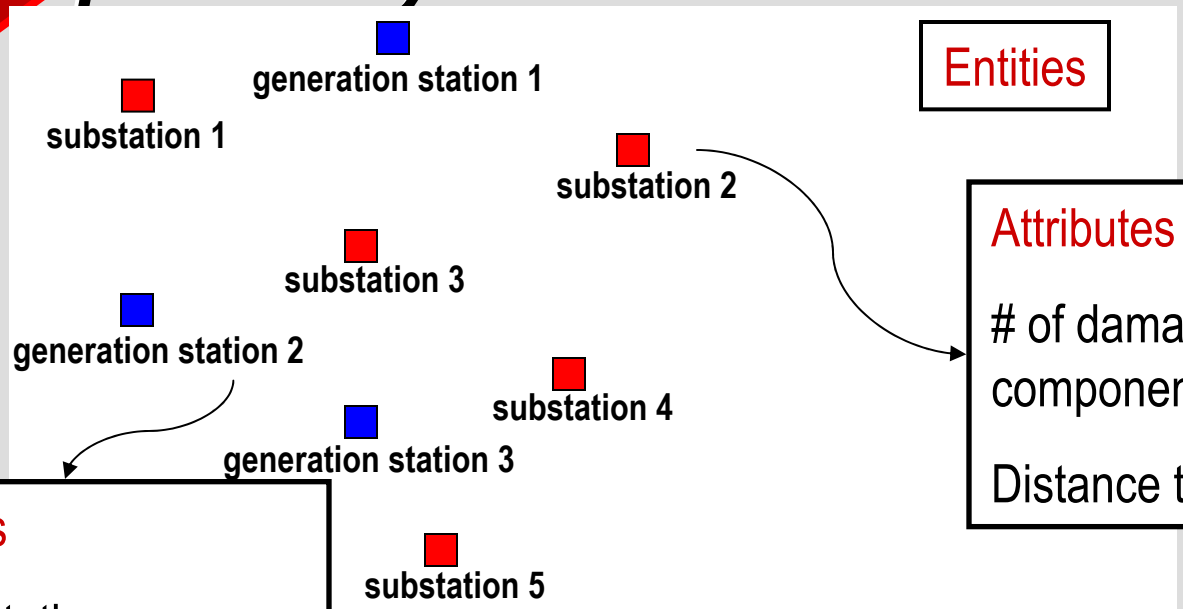
rapidity

EQ Restoration: Discrete Event Simulation



Rapidity

EQ Restoration: Discrete Event Simulation



Entities

Attributes

# of damaged components

Distance to epicenter

Attributes

Type of station

Distance to epicenter

Critical restart time limits

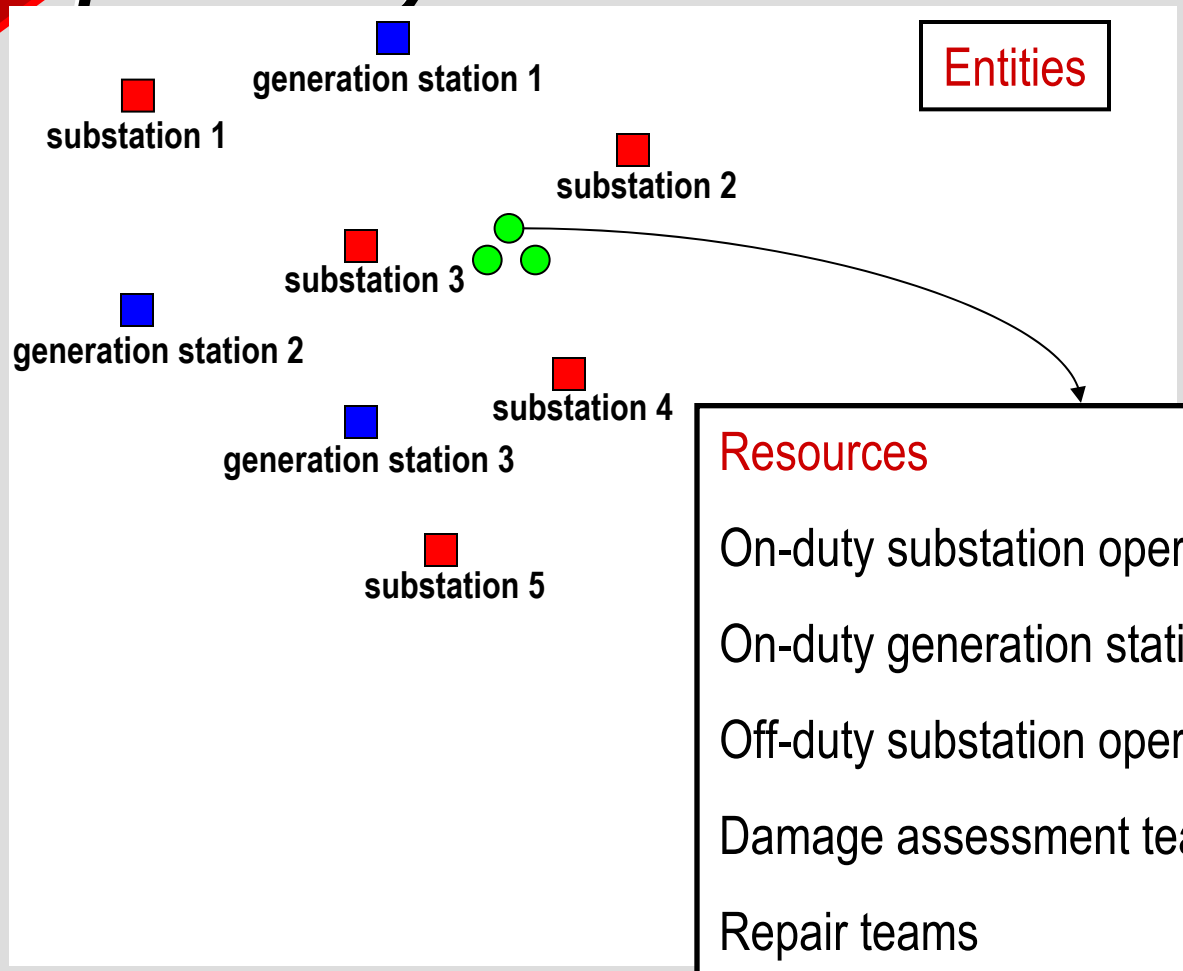
Global variables

Status of stations before & after the earthquake

Duration without power for each load bank

rapidity

EQ Restoration: Discrete Event Simulation



Resources

On-duty substation operators

On-duty generation station operators

Off-duty substation operators

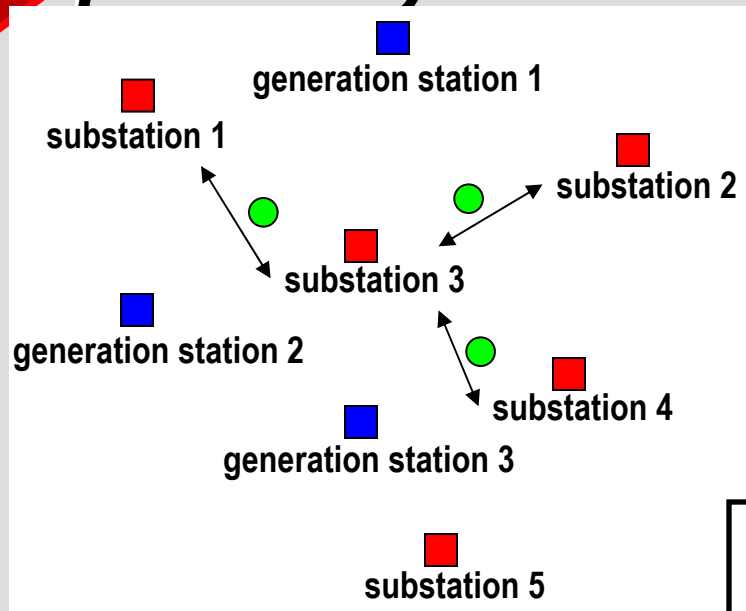
Damage assessment teams

Repair teams

Repair material of different types

Rapidity

EQ Restoration: Discrete Event Simulation



Entities

Events

Inspection

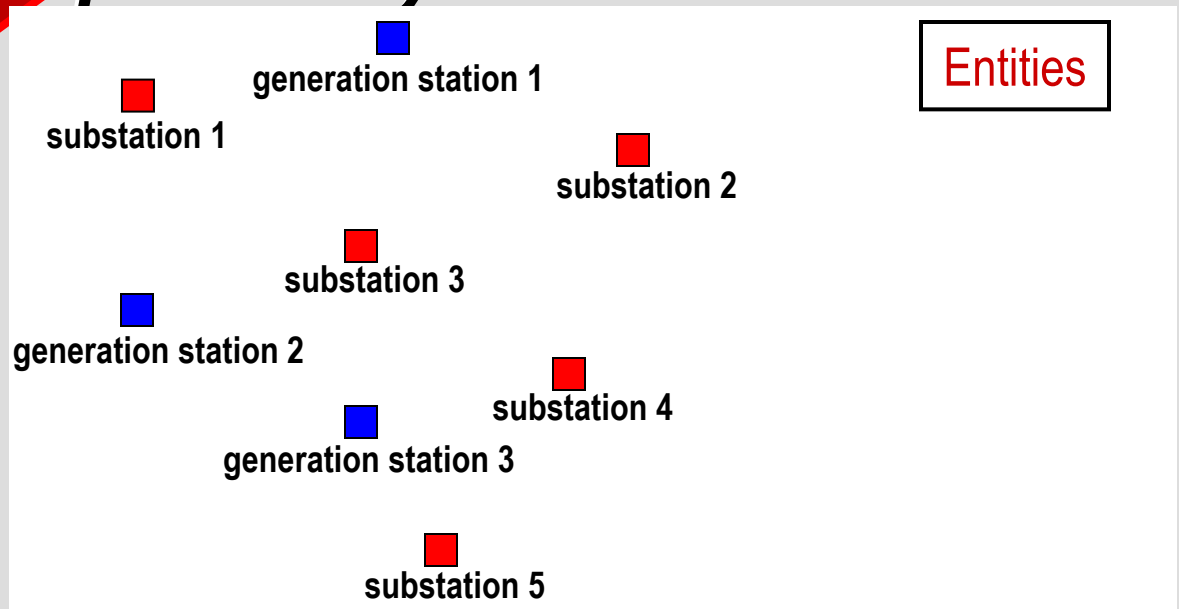
Damage assessment

Repair

Reenergizing

Rapidity

EQ Restoration: Discrete Event Simulation



As events take place, variable values get updated.
By tracking variable values as we step through time, we simulate process.

Task durations and amount of repair material are random variables
→Final restoration time is uncertain.
→Repeat process 100 times to get a pdf on restoration time.

Rapidity

Risk Assessment Method

Hazard model

47 eq scenarios
with probabilities

Damage model

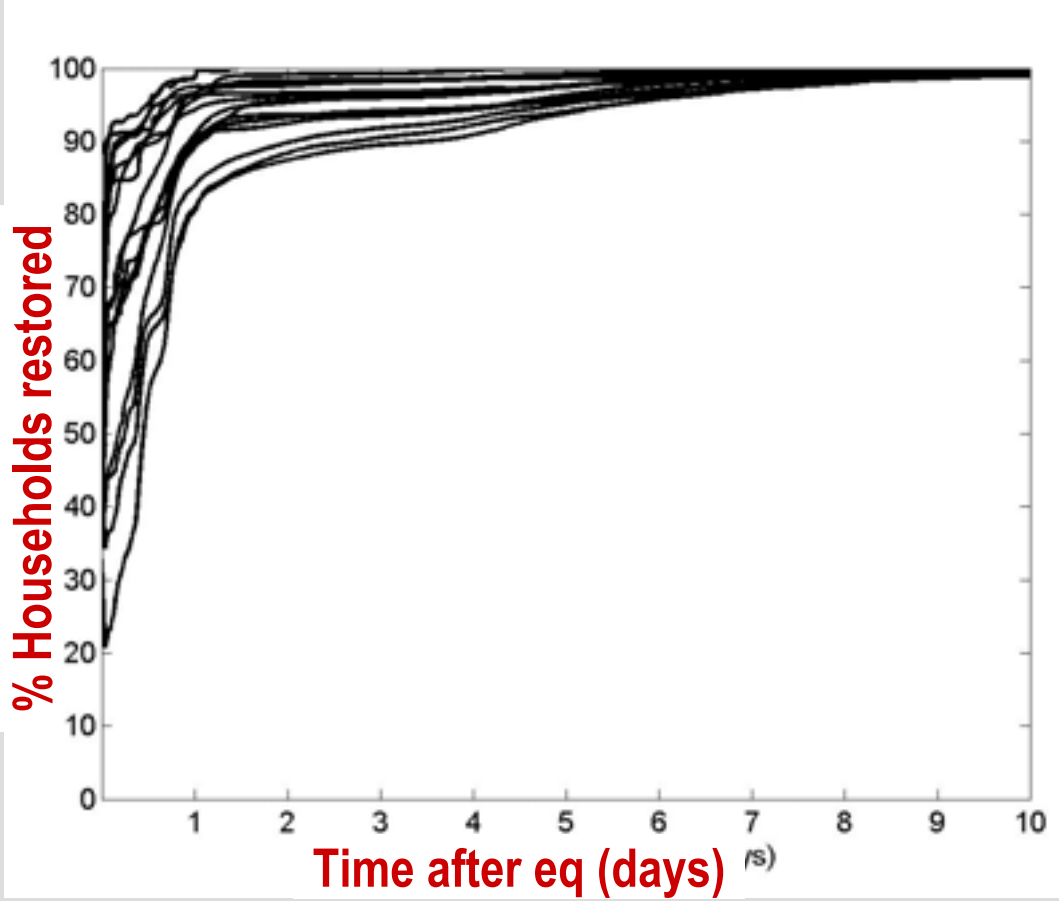
Damage
Functionality

Restoration model

Rapidity

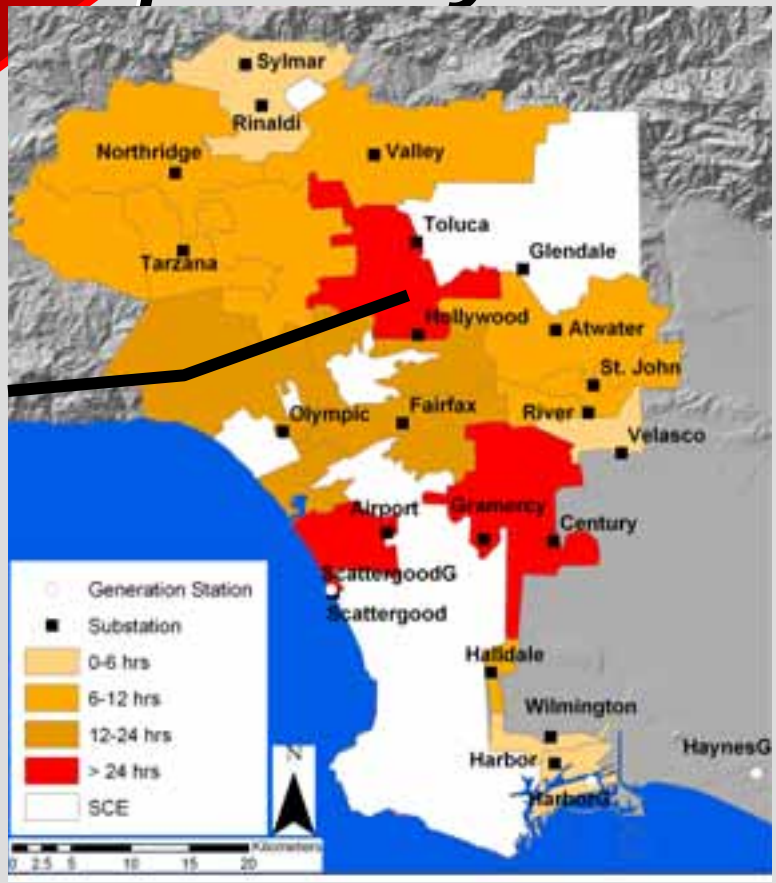
Results: Restoration Curves

Suite of restoration curves for each eq scenario-damage state

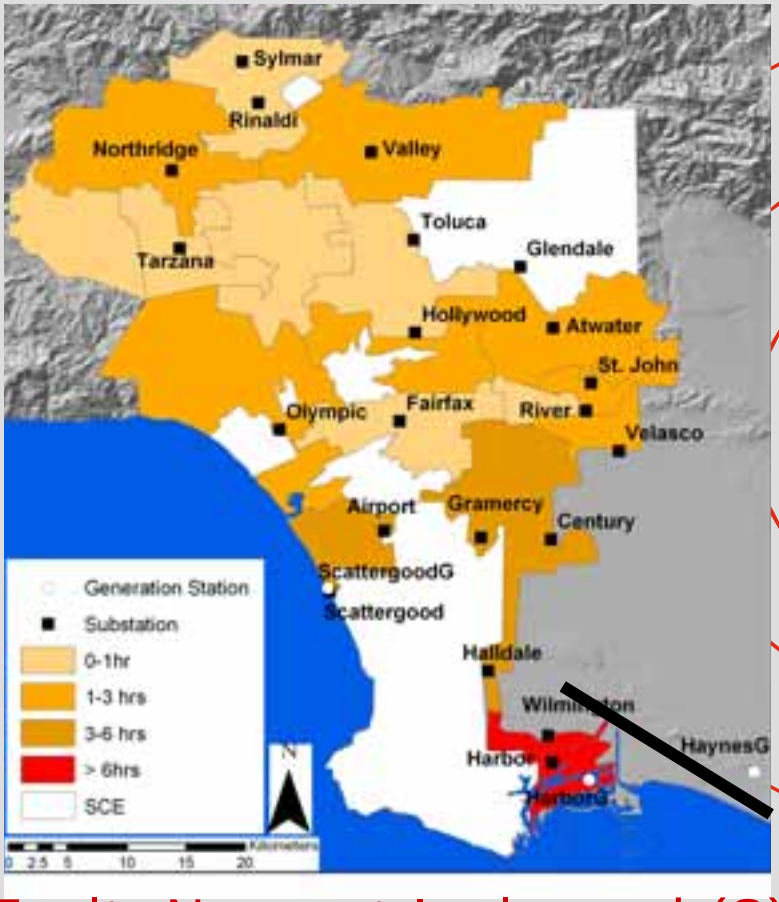


Rapidity

Results: Spatial Evolution



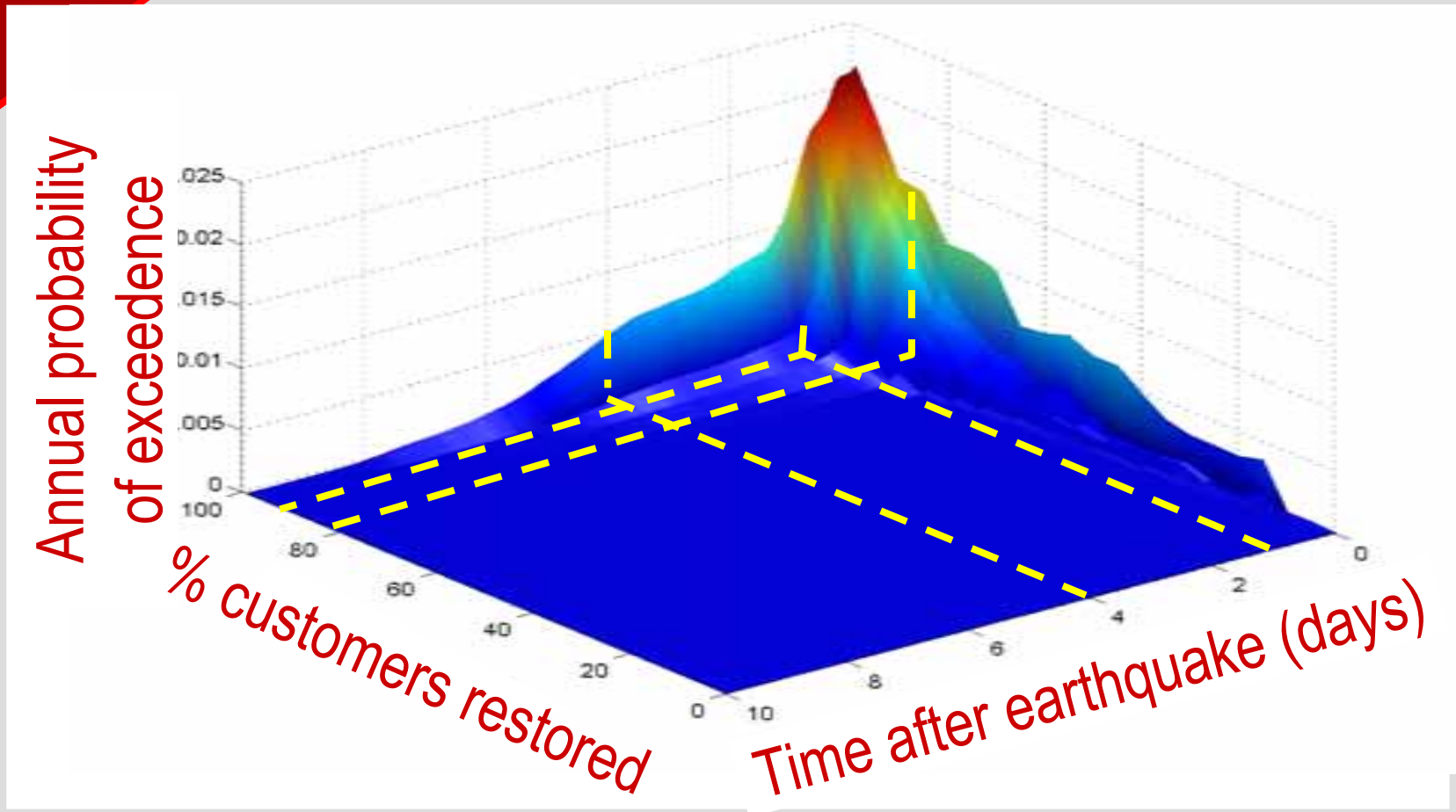
Fault: Malibu Coast



Fault: Newport Inglewood (S)

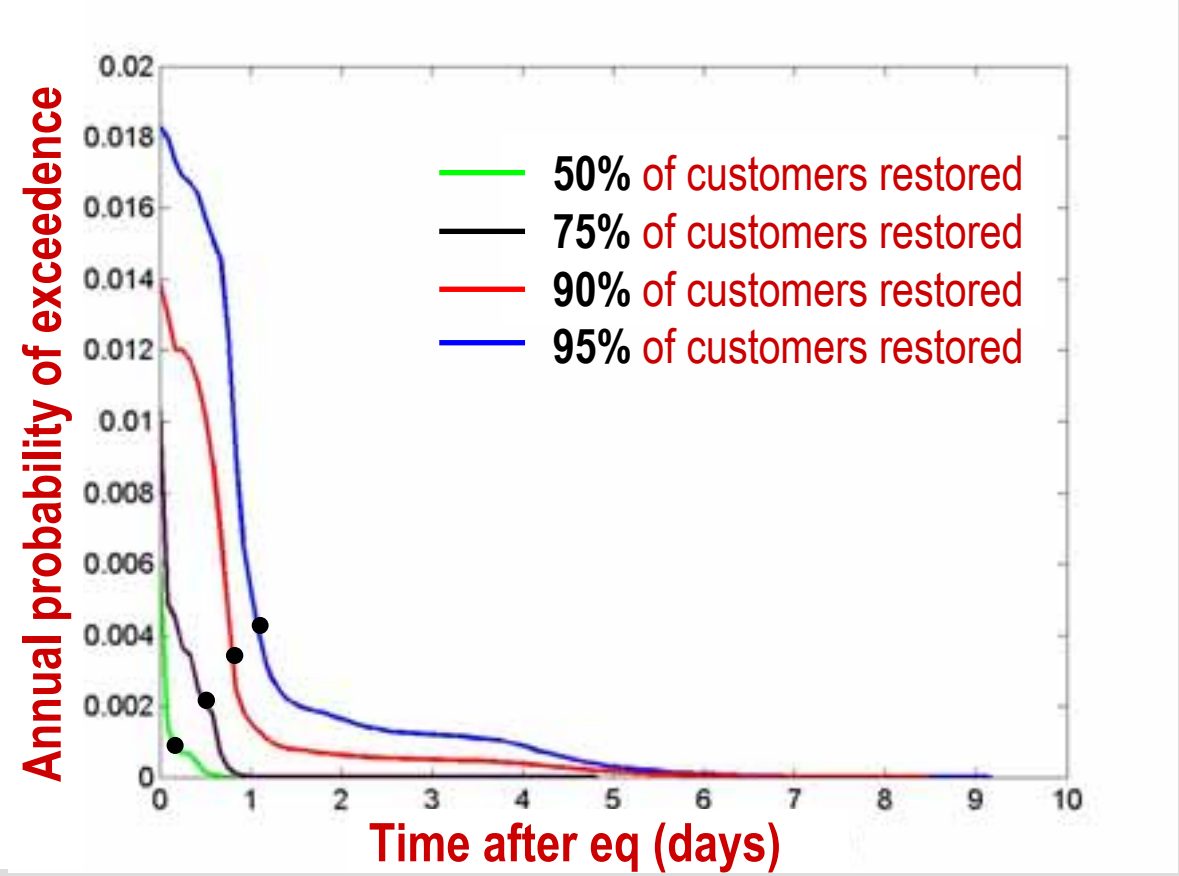
Rapidity

Results: Power Rapidity Risk Surface



Rapidity

Results: Compared to Northridge



How likely is it that 1994 Northridge eq experience will be exceeded?

In case of Northridge:

50% → 7 hrs

75% → 11 hrs

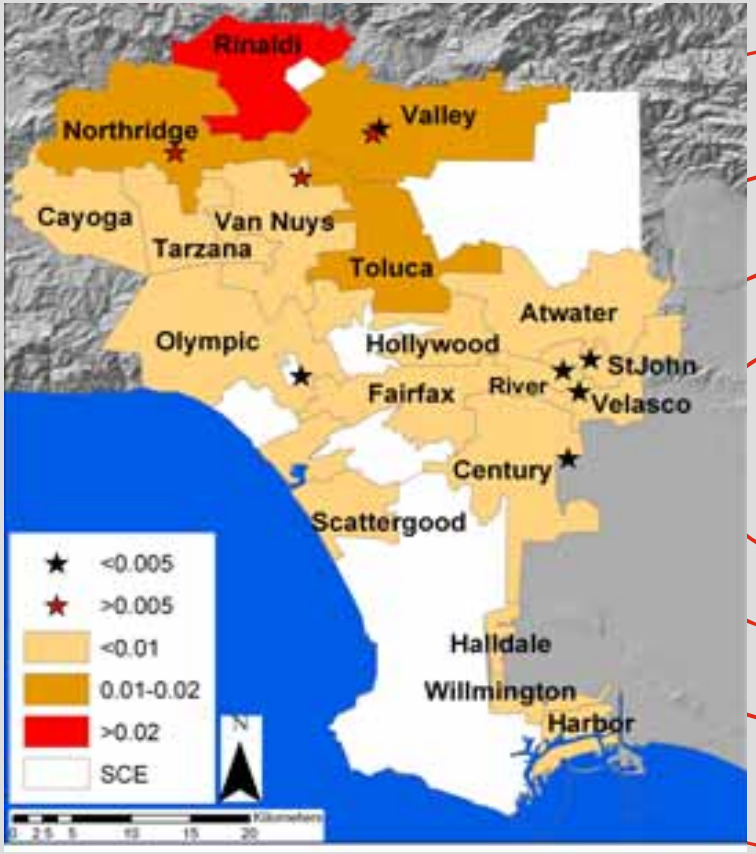
90% → 19 hrs

95% → 26 hrs

Rapidity

Results: Adequacy of Resources

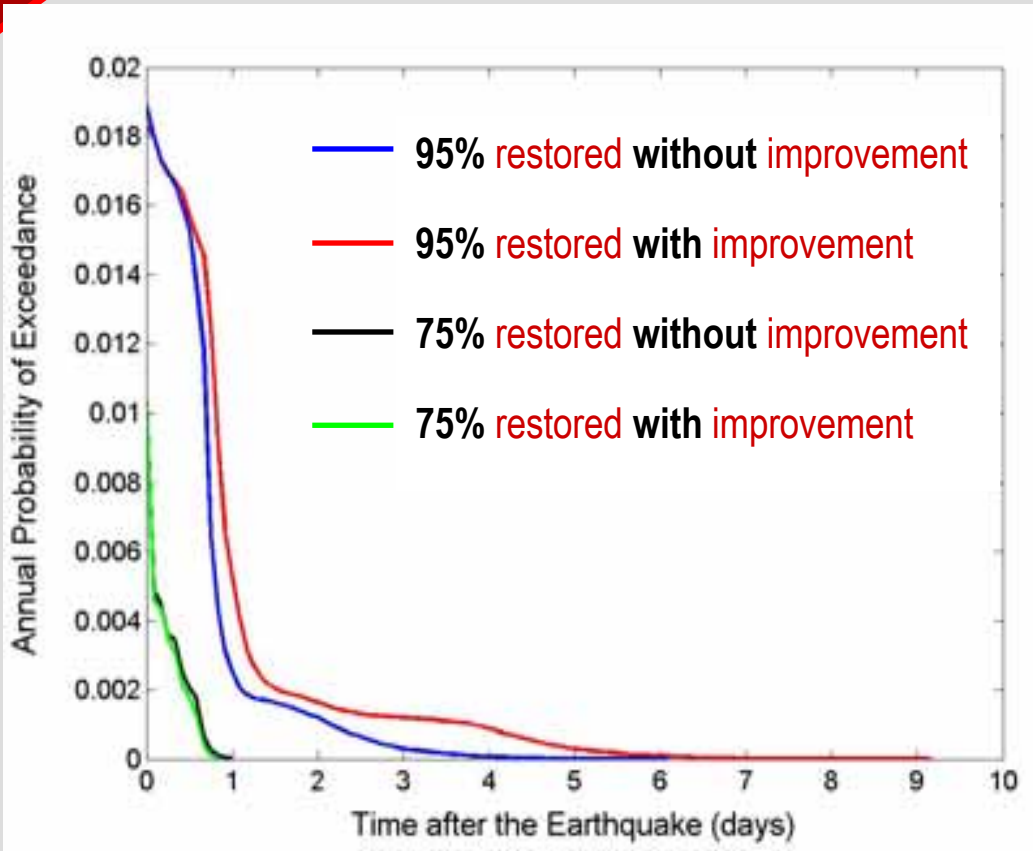
- More likely to run out of circuit breakers at substations & district yards in north
- If Malibu Coast (MCE 7.3) eq occurs, 55% chance of using all circuit breakers



Annual probability of using all circuit breakers

Rapidity

Results: Risk Curves



- Number of repair teams at critical district yards increased by 50%
- More effective in reducing long-duration power outages
- **Results differ depending on rapidity measure used**

Rapidity

2 Optimization Models

Scheduling optimization

- How to schedule inspection, damage assessment, repair tasks
- Stochastic integer program
- Genetic algorithm
- Loosely-coupled with simulation

Crew optimization

- How many inspection, damage assessment, repair teams to have and where
- Mixed-integer nonlinear program
- Genetic algorithm
- Tightly-coupled with simulation

Rapidity

Scheduling Optimization

Objective

- Minimize $SAIDI_{EQ}$ (area above restoration curve)

Decision variables

- Time each inspection (I), damage assessment (D), repair (R), reenergizing (G) task starts for each substation

Constraints

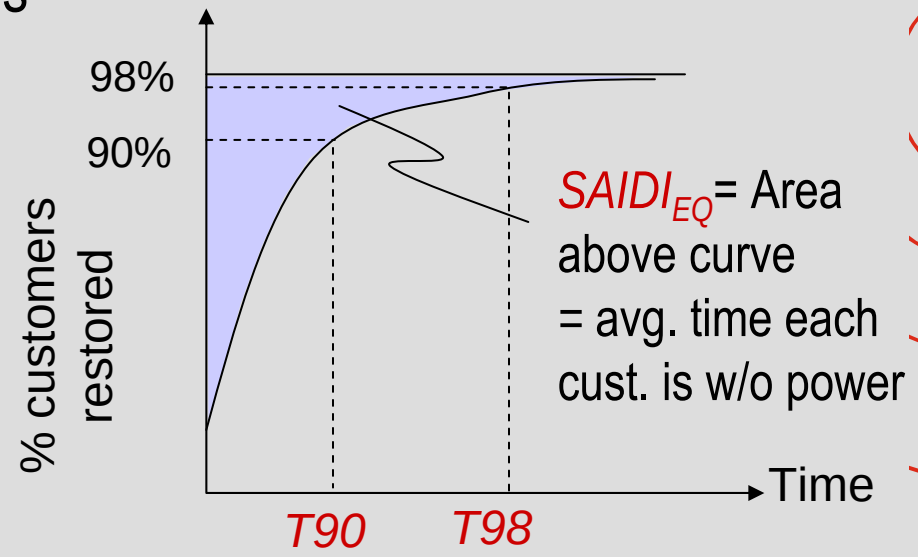
- Precedence among I, D, R, and G tasks for each substation
- All tasks must be finished at each substation
- Limited number of available I, D, R teams each time period
- Connectivity and operations of network

Rapidity

Analysis Procedure

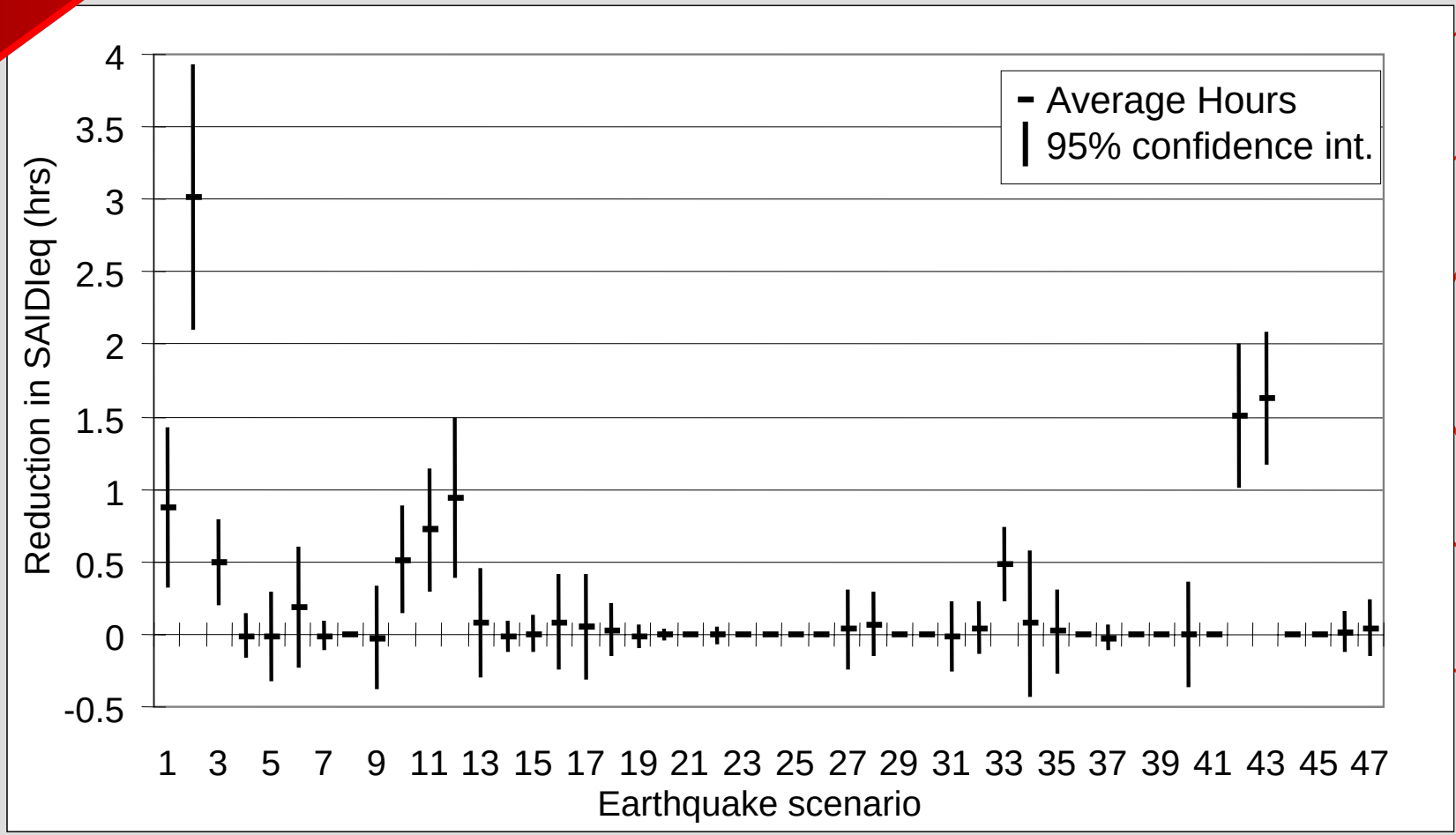
1. Run optimization to determine new “best” priorities
2. Run restoration simulation for optimization-generated and LADWP scheduling priorities for 47 eqs
3. Compare restorations using optimization-generated & LADWP priorities using 3 measures:

   $SAIDI_{EQ}$, *T90*, *T98*



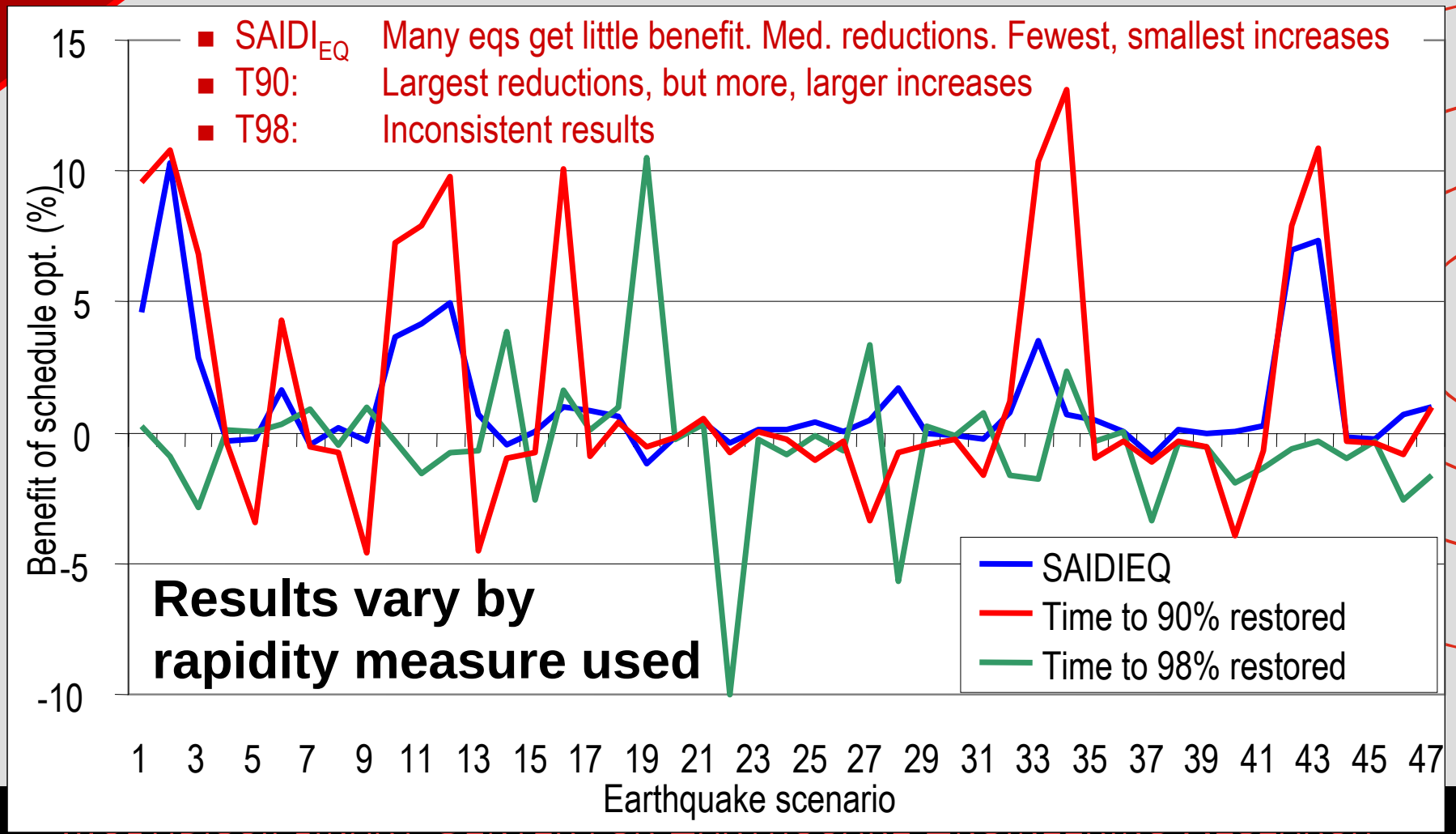
Rapidity

Benefit of Optimized Solution



Rapidity

Benefit of Schedule Optimization (%)



Rapidity

Multi-Hazard Extensions

	Earthquakes	Hurricanes / Ice storms
Geographic extent	• Counties	• Counties
Warning?	• No warning	• Few days warning
Damage	• Generation & trans., few locations (network)	• Distribution, trees, many locations (radial / loop)
Damage modeling	• Structural	• Statistical
Restoration model.	• Discrete event simulation	• Statistical (or DES)
Rest. model uses	• Loss est., evaluate restoration strategies (& inform customers)	• Inform customers (& loss est.)
To improve restor.	• Harden, procedures, crews, materials	• Harden, procedures, crews, materials

Rapidity

Hurricane & Ice Storm Restoration

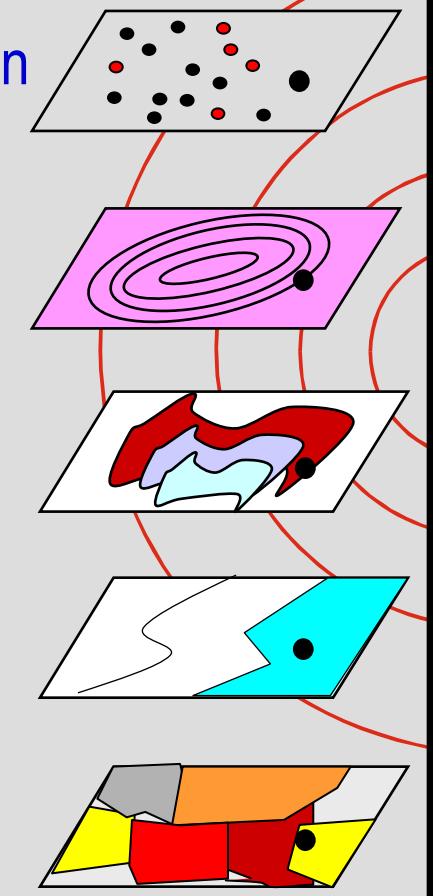
Company	Hurricanes	Ice Storms		
Dominion Virginia	Bonnie (5,079) Dennis (2,917, 1,267) Floyd (8,186) Isabel (58,393)	12/98 (10,125) 1/1/99 (1,238) 1/14/99 (2,597) 1/00 (2,687)	12/00 (638) 12/5/02 (1,484) 12/11/02 (1,464) 12/25/02 (468)	2/03 (1,095) 3/03 (375)
Duke	Opal (1,970) Fran (1,818) Floyd (1,061) Isabel (2,009)	2/96 (4,163) 1/99 (2,705) 12/02 (13,370) 2/03 (3,277)		
Progress Carolinas	Bonnie (2,746) Dennis (1,623) Floyd (11,505) Isabel (13,572) Charley (3,470)	1/04 (7,449)		

150,000+ outages in total

Rapidity

Method

- Overlaid all data in GIS
- Found covariate values for each outage
- Fit statistical models to relate outage durations to storm, system, land characteristics
- Simulate restoration times



Rapidity

Survival Analysis

- **Regression when response is time**

  Nonnegative, often negatively skewed

  (censoring, conditioning)

- **Accelerated failure time (AFT)**

  $\ln(T)=\mathbf{x}\beta + \varepsilon$

  Like ordinary regression, but ε not necessarily Normal

- **Cox proportional hazard (CPH)**

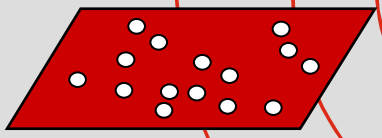
  $h(t)=h_0(t)\exp(\mathbf{x}\beta)$

Rapidity

Outage Duration to Restoration Times

For each county (or other area unit)

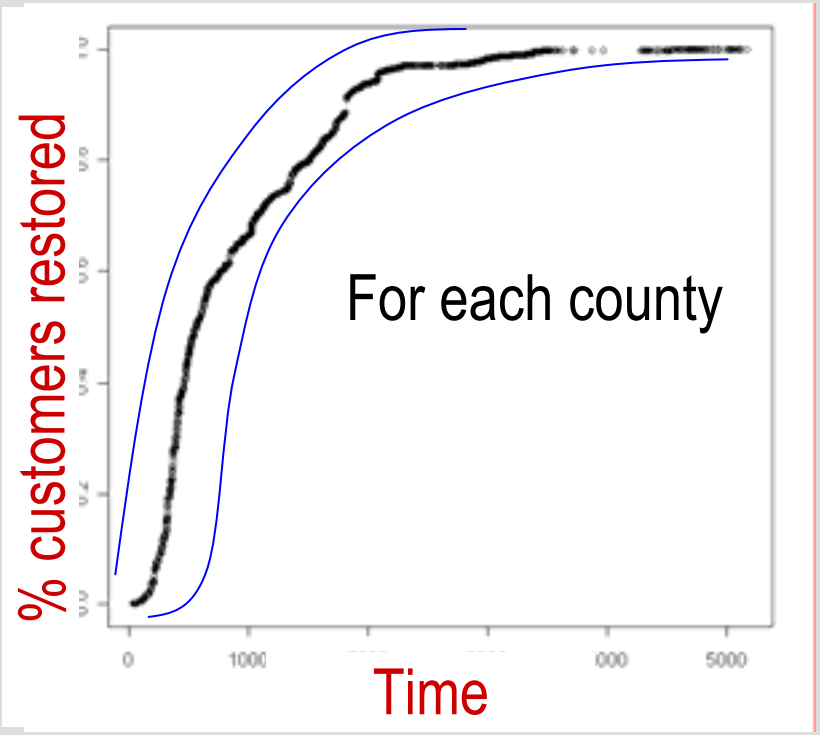
- For each outage
  - Sample covariate values & outage start time (or take from Outage Mgmt. System)
  - Sample outage duration using AFT model
  - Restoration time = start time + duration
- Calculate t_X = time X% of customers in county are restored
- Simulate to get pdf of t_X

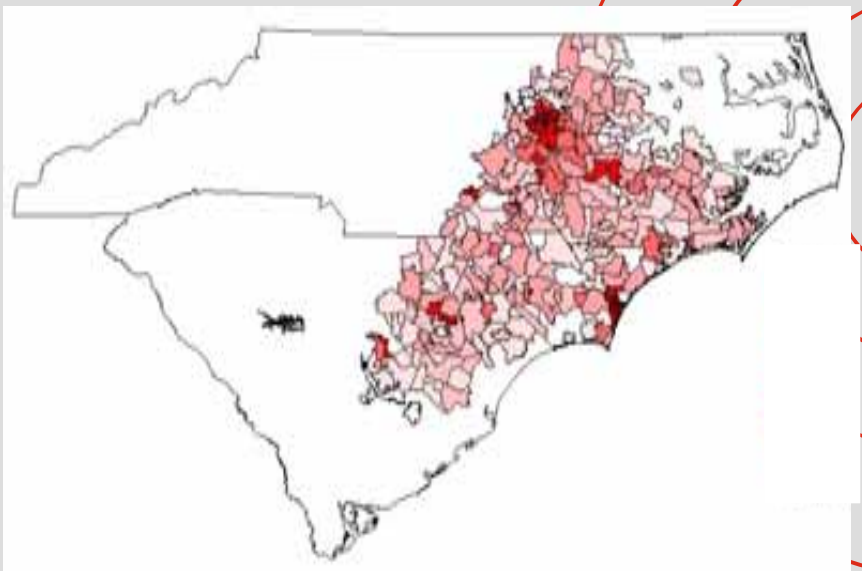


Rapidity

Output

As storm approaches,
apply model to restoration curve for each zip code





Estimated time to restore X%
of customers

Rapidity

Data Envelopment Analysis (DEA)

- Compares efficiency of organizational units relative to "best" org. units when multiple inputs and outputs.
- Given controllable and uncontrollable inputs, based on other units, could organizational unit produce more output?
- Linear programming formulation

Power restoration application

• Organizational units	Storm-company event
• Outputs	Measures of rapidity, e.g., $SAIDI_{EQ}$
• Controllable inputs	Restoration expenditures
• Uncontrollable inputs	Storm severity, damage

Rapidity

Electric Power Rapidity Summary

Measures of rapidity

- Restoration curve
  - Time to restore X% of customers
  - $SAIDI_{EQ}$
- Spatial evolution of rapidity
- Rapidity risk surface / curve
- Resources used
- vs. past event (e.g., Northridge EQ)
- vs. when restoration is changed
- vs. optimized “best” restoration
- Relative efficiency vs. other events

Analysis methods

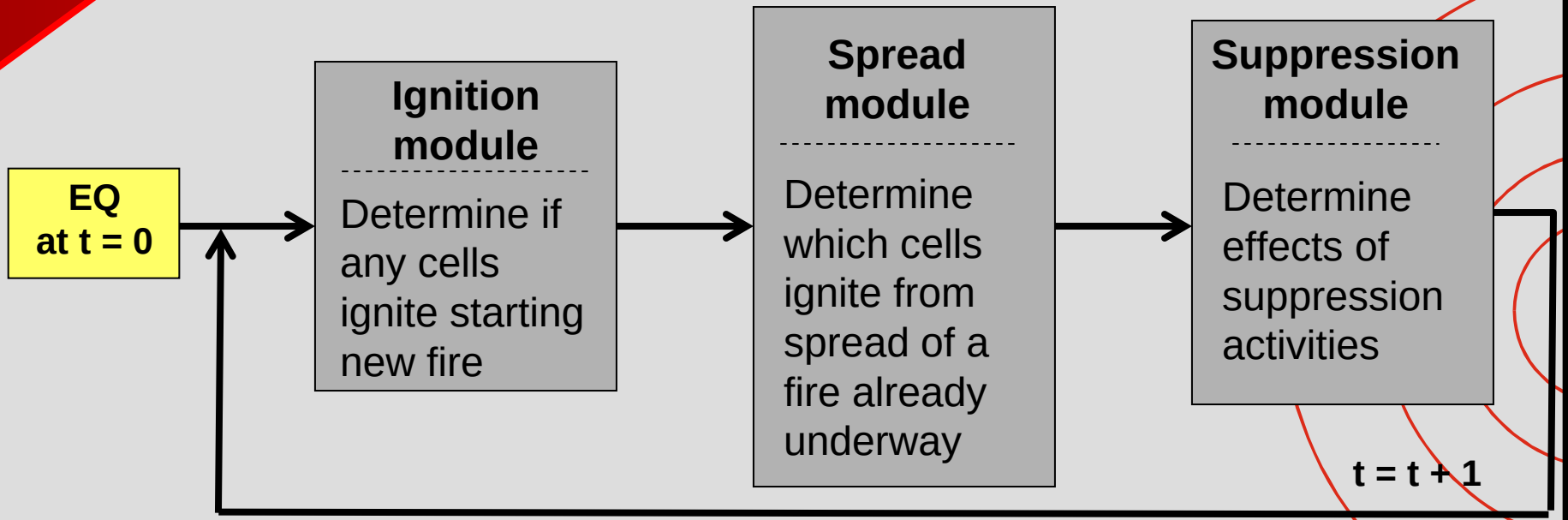
- Discrete event simulation
- Optimization
- Statistics / survival analysis
- Data envelopment analysis

Hazards

- Earthquakes
- Hurricanes
- Ice storms

Rapidity

Fire Following Earthquake



- **Discrete event simulation** (suppression)
- **Cellular automata** (spread)
- **Incorporation of MCEER lifeline results** (all)

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