Grid Resilience: Design and Restoration Optimization

LA-UR-14-25832

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joint work with

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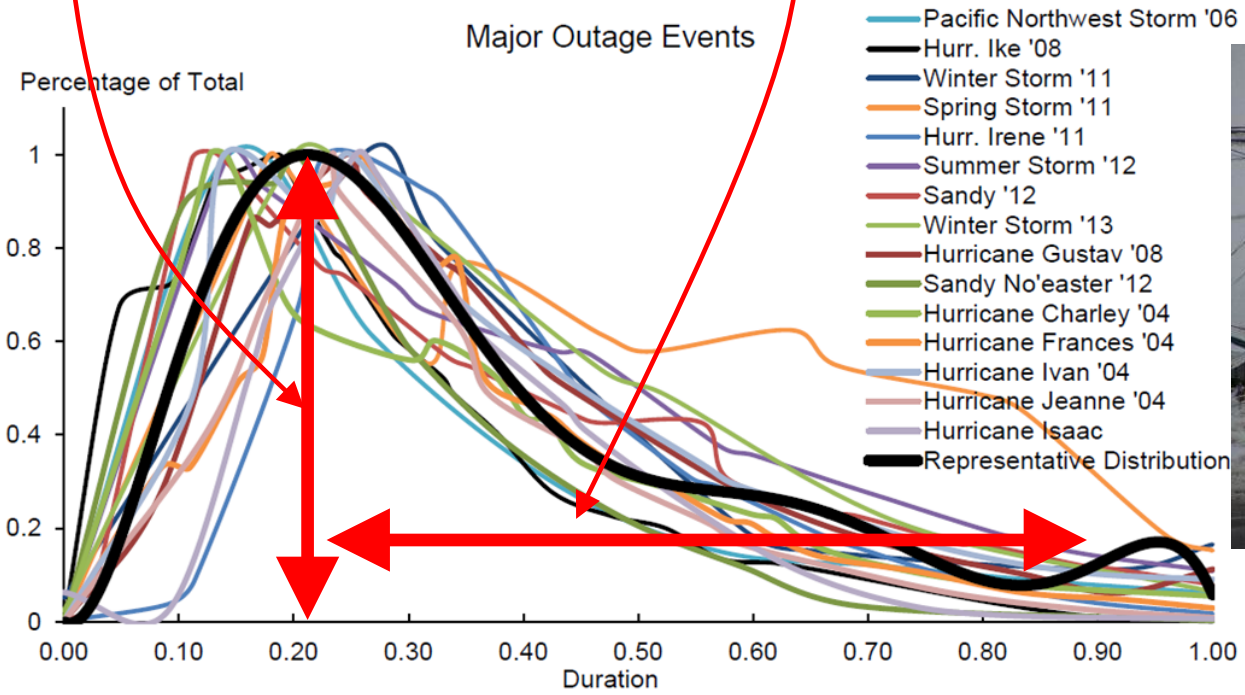
What is Resilience

Presidential Policy Directive - Critical Infrastructure Security and Resilience

"The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents."



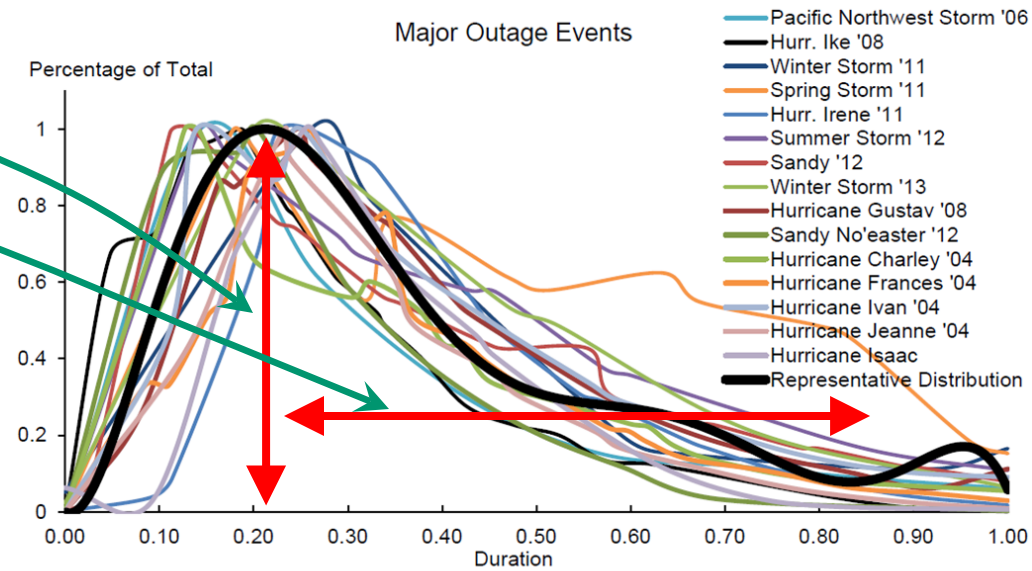
Source: Department of Energy, Office of Electrcity Delivery and Energy Reliability

Our Goals

<u>Develop new tools, methodologies, and algorithms to enable the design of resilient power distribution systems</u>

Hardening/Resilience options

- *Asset hardening*
- *System design*
- *System operations*
- *Repair scheduling*
- *Emergency operations*



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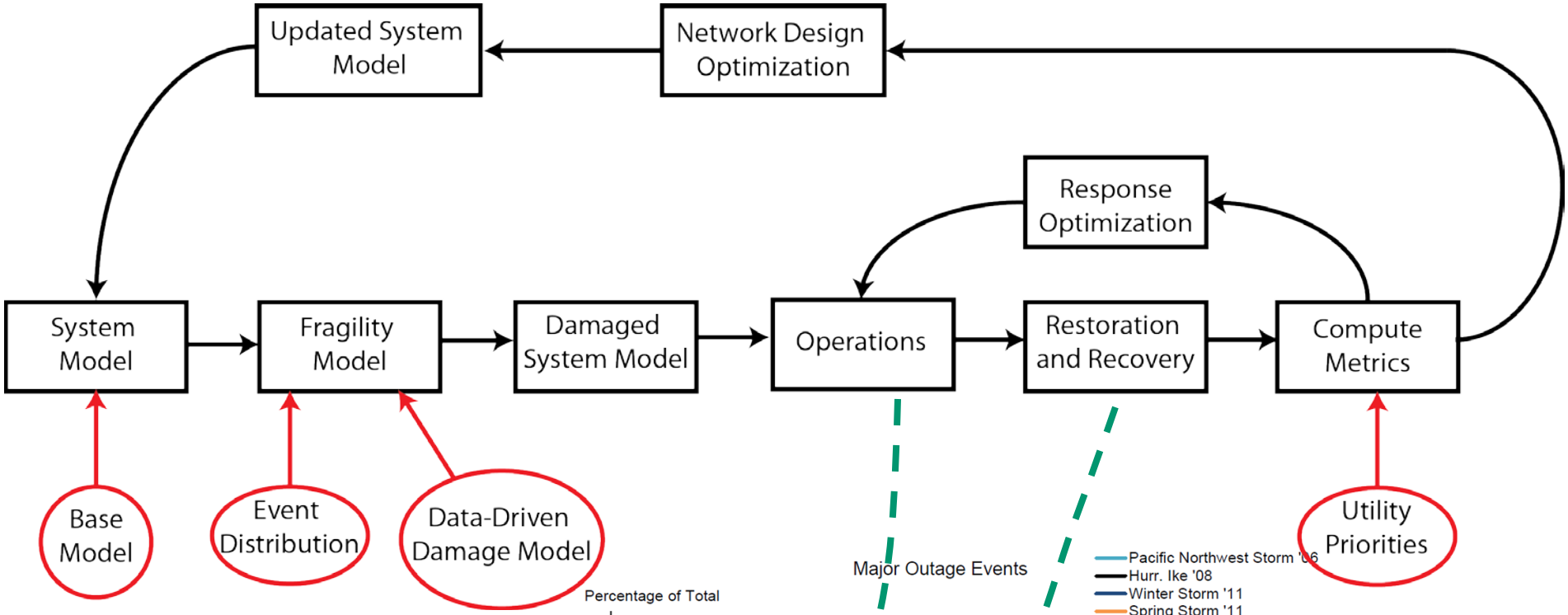
Flexibility for the user

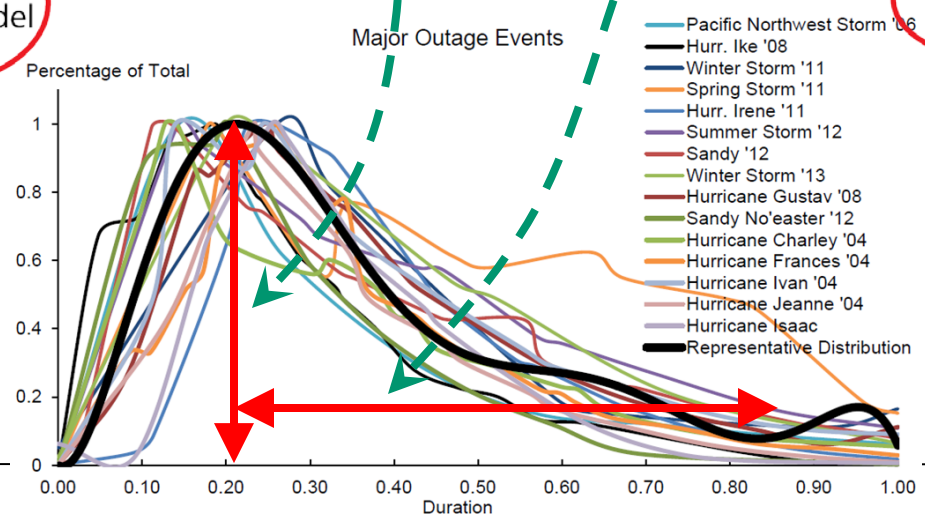
- *User's base network model*
- *User-defined resilience metrics*
- *User suggests upgrades*
- *User-defined costs*
- *User-defined threat and scenarios*

Capabilities

- *Assess current resilience posture*
- *Optimize over user-suggested upgrades to improve resilience considering budget*

Resilience Design Process Flow—End Goal





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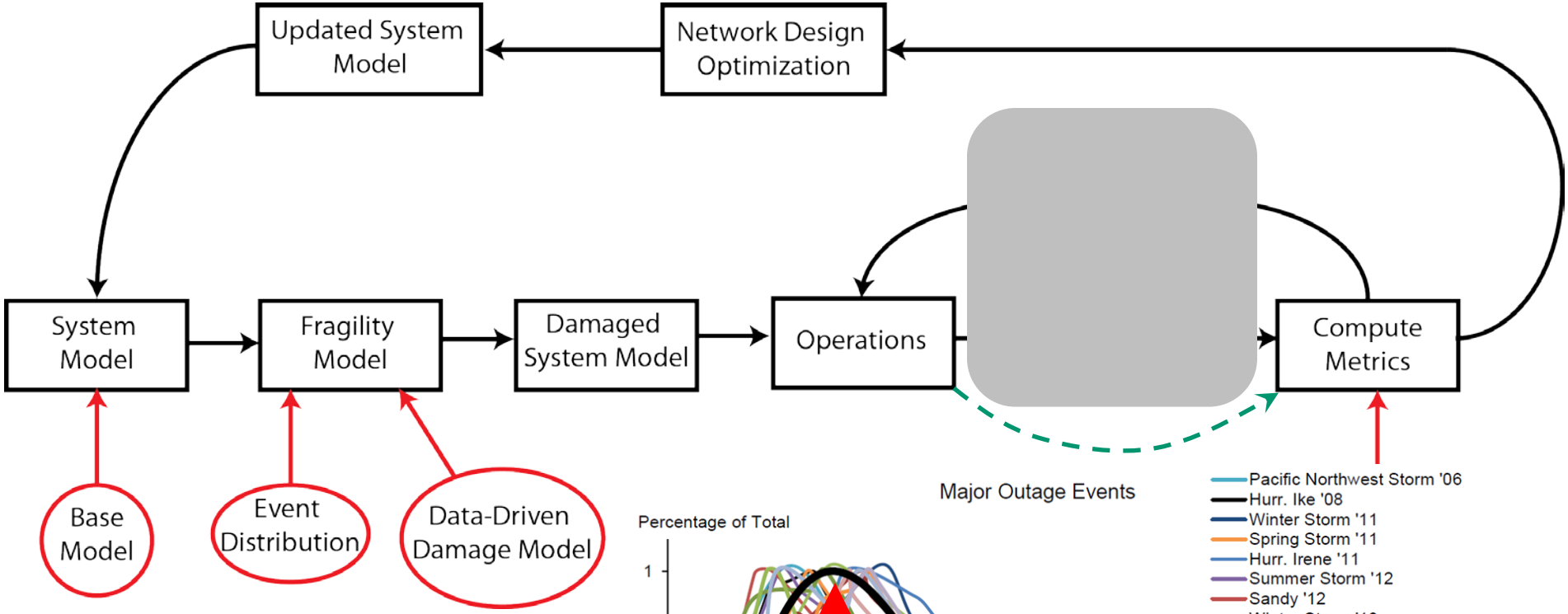
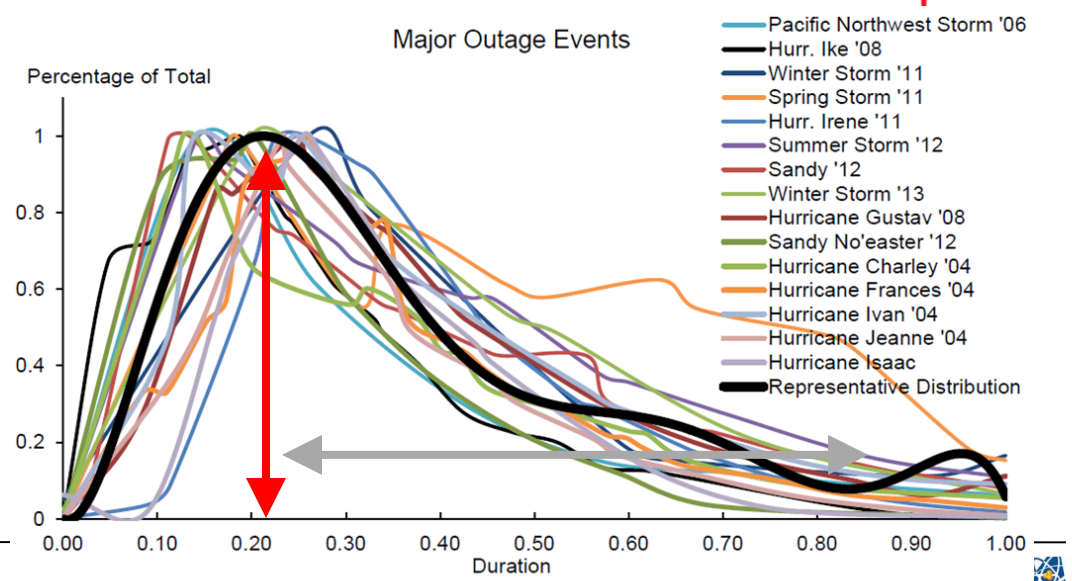
Resilience Design Process Flow—Today



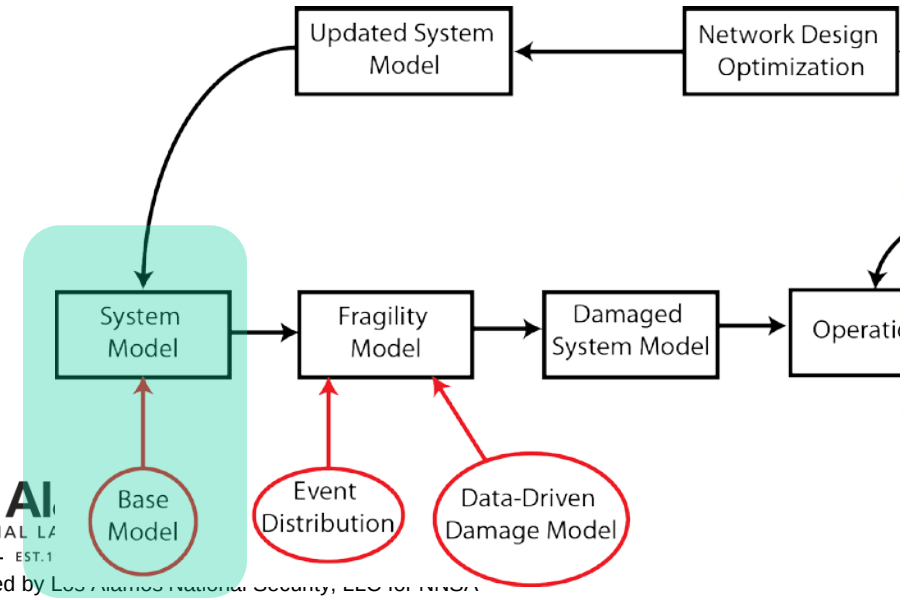


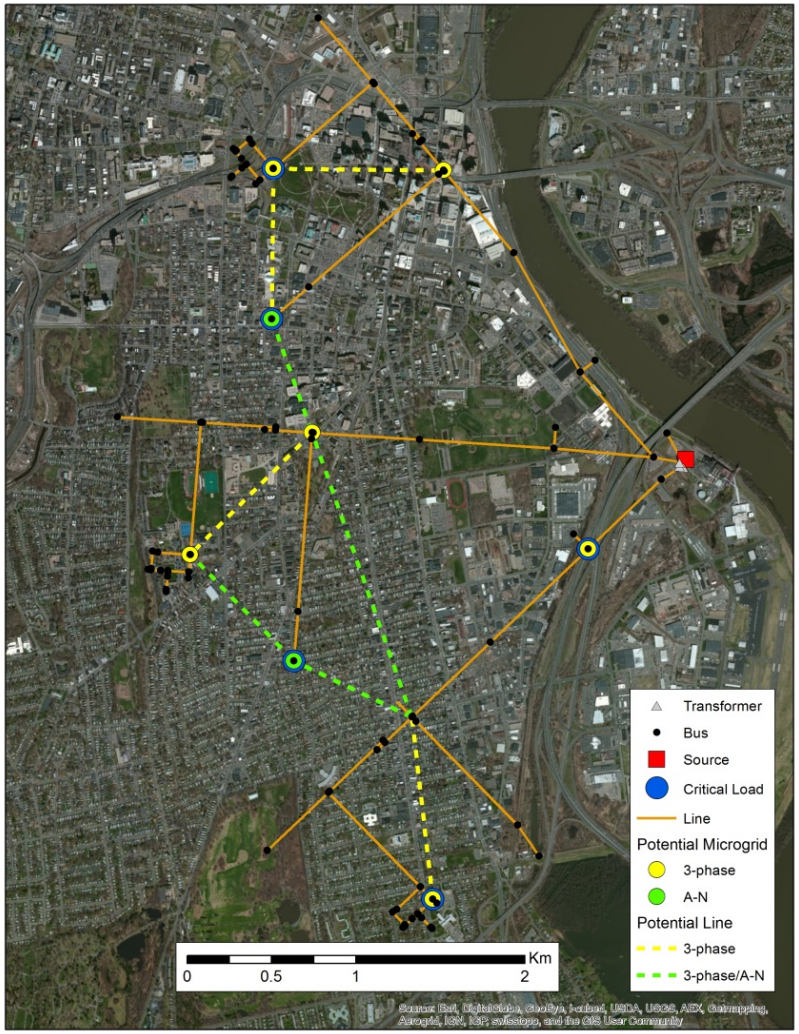
Source: Department of Energy, Office of Electrcity Delivery and Energy Reliability

Resilience Design Process Flow—System Model

Flexibility for the user

- *User's base network model*
- *User-defined resilience metrics, e.g. critical load service*
- *User suggests upgrades*
- *User-defined costs*
- *User-defined threat and scenarios*





Resilience Design Process Flow—Direct Impacts

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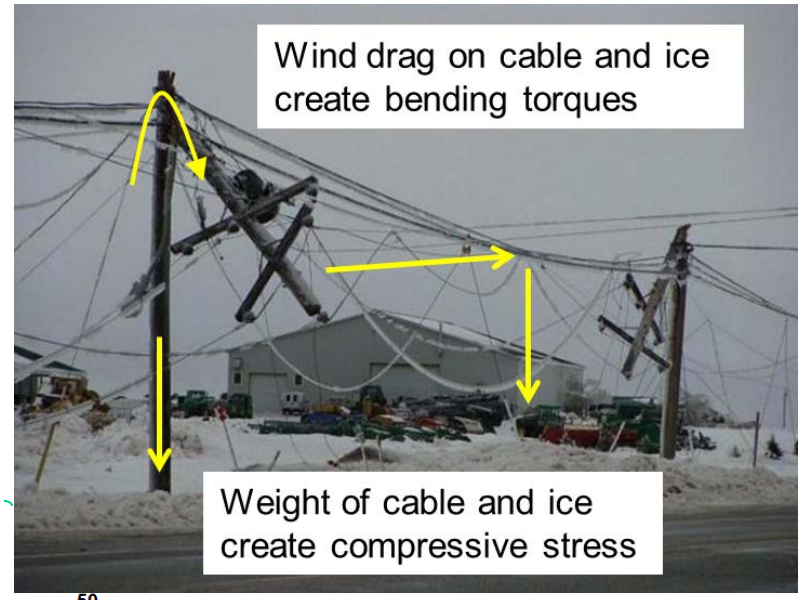
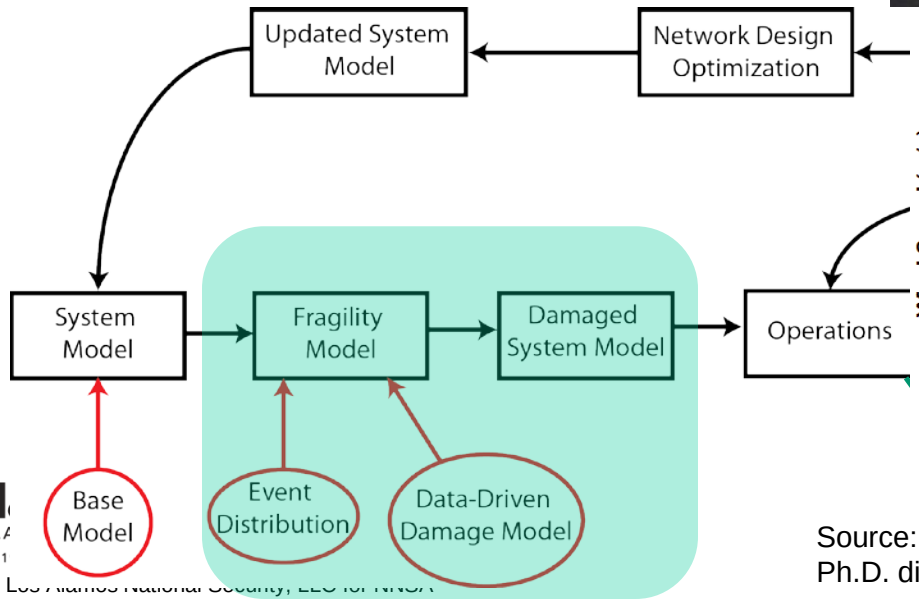
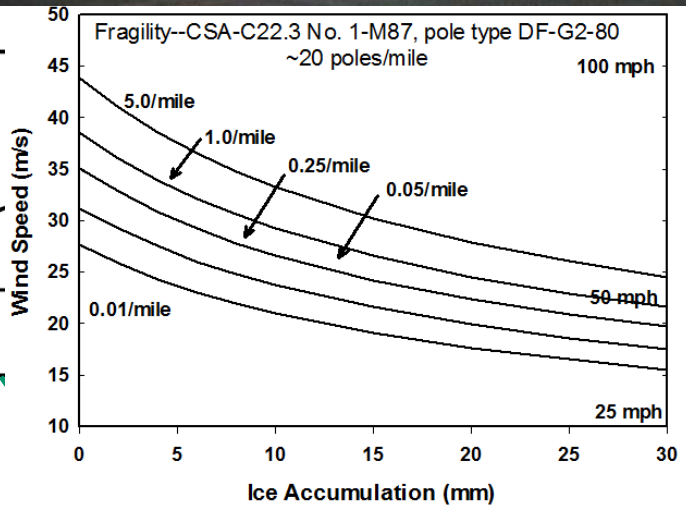
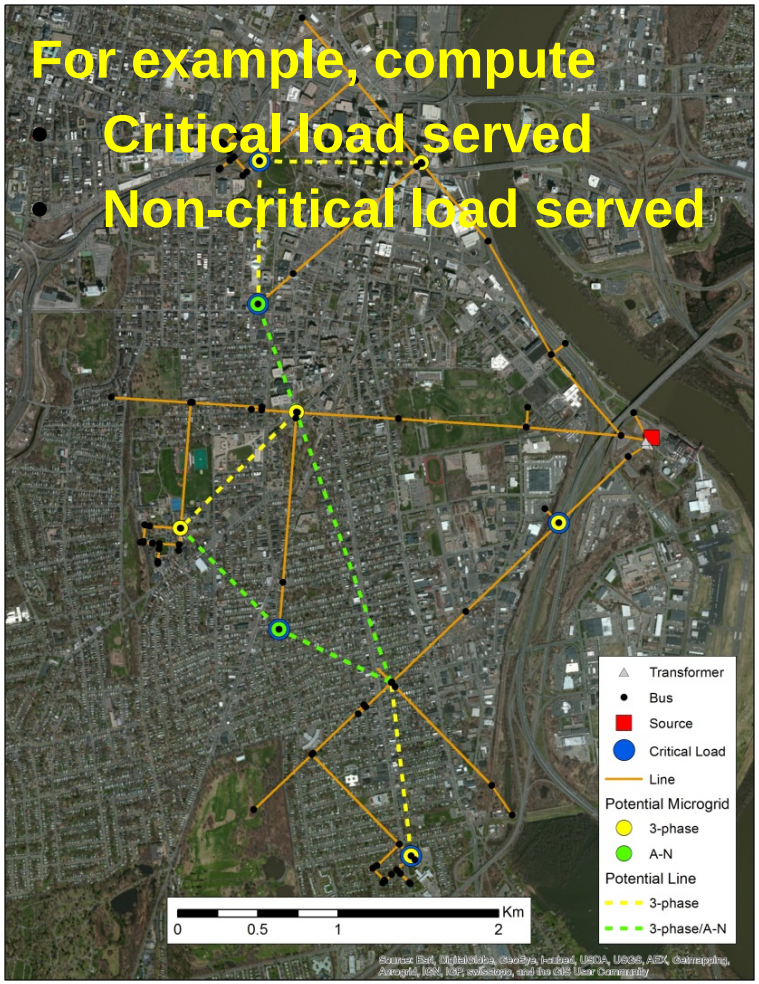






Source: Y. Sa, *Reliability analysis of electric distribution lines* Ph.D. dissertation, McGill University, Montreal, Canada, 2002

Resilience Design Process Flow—Secondary



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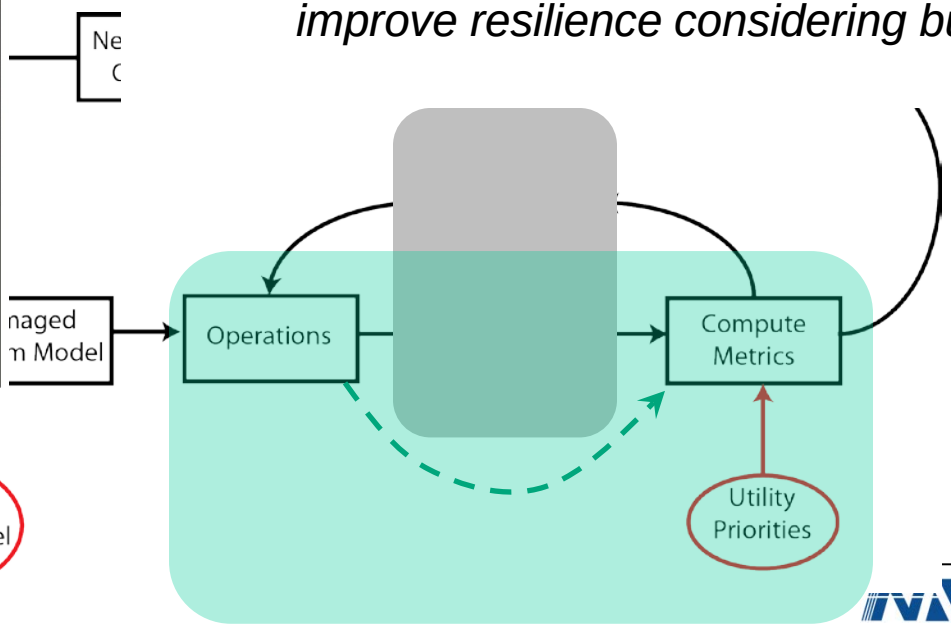


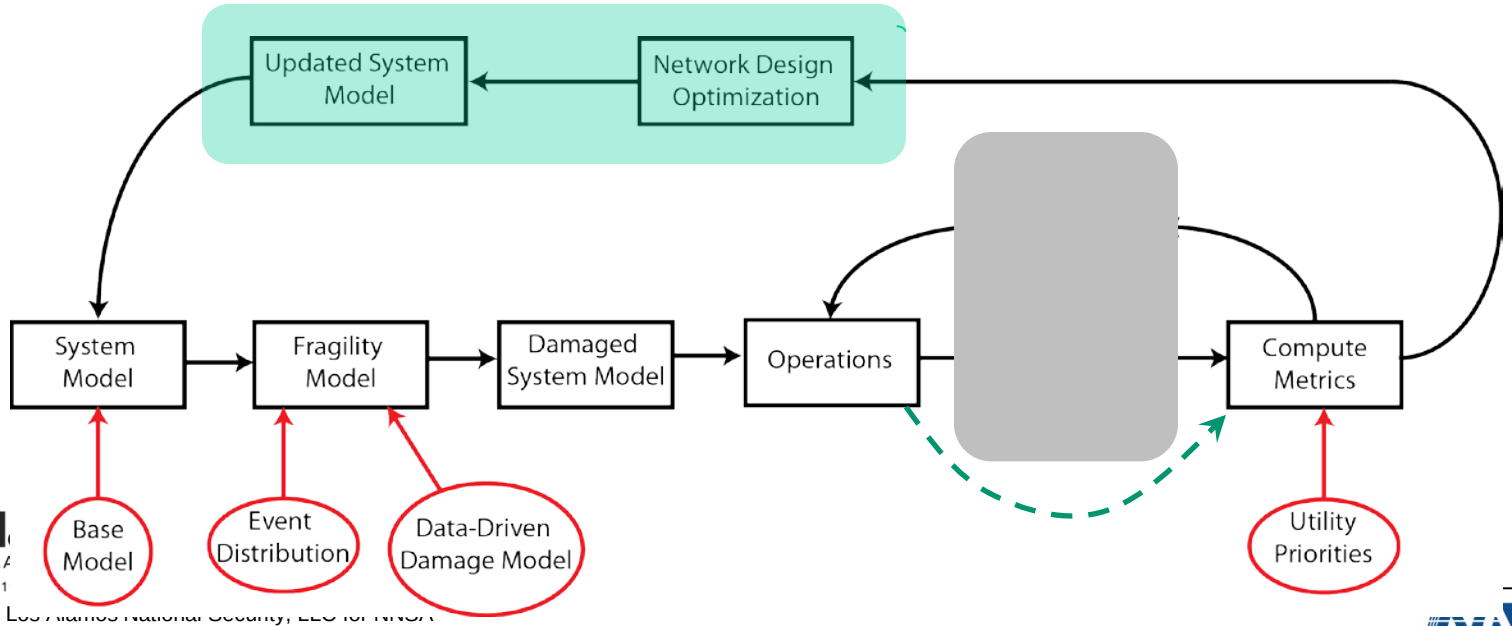
Base Model

Event Distribution

Data-Driven Damage Model

Resilience Design Process Flow—Design Network

- Hardening/Resilience options
  - *Asset hardening*
  - *System design*
  - *System operations*
  - *Repair scheduling*
  - *Emergency operations*
- Capabilities
  - *Assess current resilience posture*
  - *Optimize over user-suggested upgrade to improve resilience considering budget*



Design Network—Hardening/Resilience Options

Add distributed generation in microgrids:

- Natural gas generators and/or CHP
- Diesel generators

Add (3-phase or 1-phase) inter-ties between:

- Distribution circuits
- Loads
- Distributed generators
- Above ground(damageable) or underground

Add switches (manual or automatic) to:

- Reconfigure circuits
- Shed circuits and/or loads

Harden existing components

- Reduce damage probabilities

Design Network—Optimization

minimize $\sum_{ij\in E} c_{ij}x_{ij} + \sum_{i,j\in E} \kappa_{ij}\tau_{ij} + \sum_{i\in N,k\in p_i} \zeta_i^k z_i^k + \sum_{i\in N} \mu_i u_i + \sum_{ij\in E} \alpha_{ij} t_{ij}$

s.t. $-x_{ij}^s Q_{ij}^k \le \sum_{k\in p_{ij}} f_{ij}^{sk} \le x_{ij}^s Q_{ij}^k$

$-(1-\tau_{ij}^s)\, Q_{ij}^k \le \sum_{k\in p_{ij}} f_{ij}^{ks} \le (1-\tau_{ij}^s)\, Q_{ij}^k$

$-\beta_{ij} \frac{\sum_{k\in p_{i,j}} f_{ij}^{ks}}{|p_{ij}|} \le f_{ij}^{k's} - \frac{\sum_{k\in p_{i,j}} f_{ij}^{ks}}{|p_{ij}|} \le \beta_{ij} \frac{\sum_{k\in p_{i,j}} f_{ij}^{ks}}{|p_{ij}|}$

$x_{ij}^s \le x_{ij},\ \tau_{ij}^s \le \tau_{ij},\ t_{ij}^s \le t_{ij},\ z_{ij}^{sk} \le z_i^k,\ u_i^s \le u_i$

$z_i^k \le M_i^k u_i,\ x_{ij}^s = t_{ij}^s,\ x_{ij}^s \le \overline{x}_{ij}^s,\ \tau_{ij}^s \le x_{ij}^s$

$3 - x_{ij}^s - \overline{\tau}_{ij}^s \ge \tau_{ij}^s \ge x_{ij}^s + \overline{\tau}_{ij}^s - 1$

$\mathrm{l}_{\mathrm{i}}^{\mathrm{ks}} = y_i^s d_i^k$

$0 \le g_i^{sk} \le z_i^{ks} + g_i^{k^+}$

$\mathrm{g}_{\mathrm{i}}^{\mathrm{ks}} - l_i^{ks} - \sum_{j\in N} f_{ij}^{ks} = 0$

$0 \le z_i^{ks} \le u_i^s Z_i^k$

$\sum_{ij\in s} \left(\overline{x}_{ij}^s + (1-\overline{\tau}_{ij})\right) \le |s| - 1$

$\sum_{i\in CL,k\in p_i} l_i^{ks} \ge \lambda \sum_{i\in CL,k\in p_i} d_i^k$

$\sum_{i\in N\setminus L,k\in p_i} l_i^{ks} \ge \gamma \sum_{i\in N\setminus L,k\in p_i} d_i^k$

$x, y, \tau, u, t \in \{0,1\}$

<u>Key Features</u>

- Least cost design for a set of scenarios
- Three-phase real power flows
- Enforces radial operations
- Enforces phase balance
- Discrete variables for load shedding (per scenario), line switching (per scenario), capital construction (first stage)

- Understand the boundaries of tractability
- Optimality vs. computation tradeoff

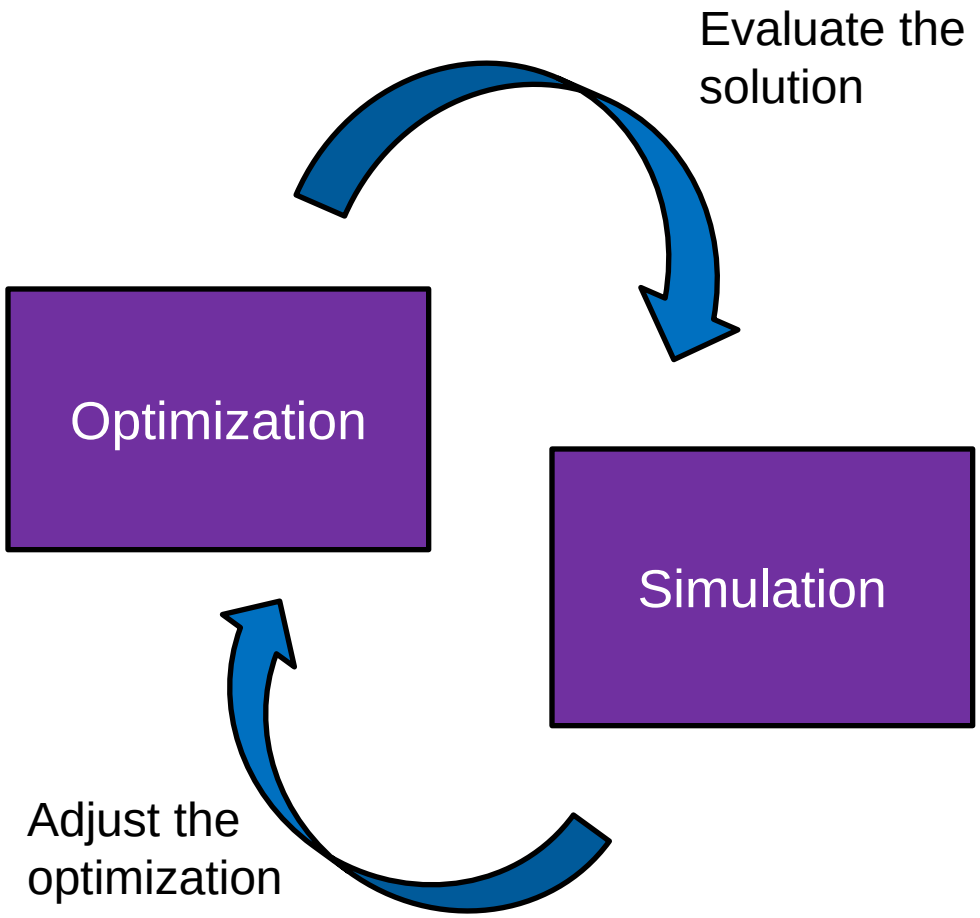
Design Network—Optimization Philosophy

Derive simplified models of power system behavior that are tractable to optimize

Linear programming, convex programming, mixed integer programming, mixed integer non linear programming, heuristics, etc.

Verify solution with a trusted power system simulation

Adjust optimization model



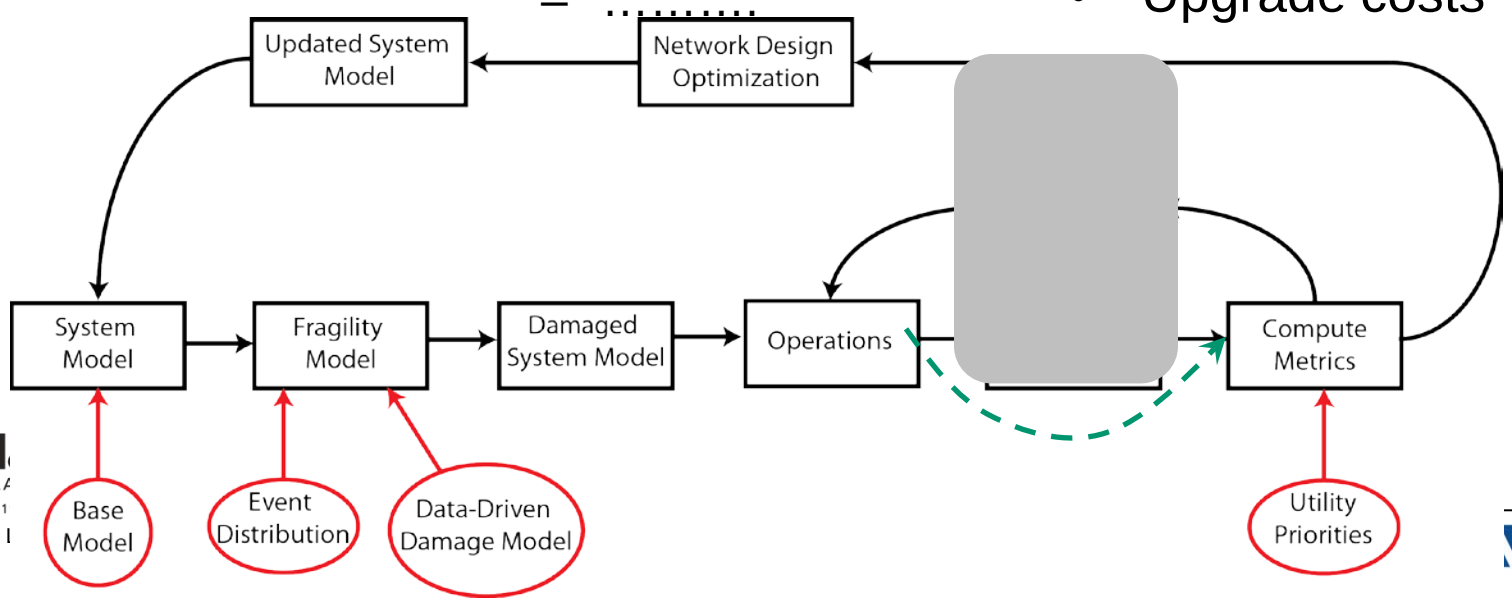
Implementation of "Withstand"—User Data Inputs

Power system model

- Base model
- Resilience upgrade options
  - Microgrids/DG
  - Asset hardening
  - New intertie lines
  - New switches

- Damage scenarios
  - Fragility models
  - Events
- Operational constraints
  - Radial
  - Phase balance
  - Voltage limit
  - ……

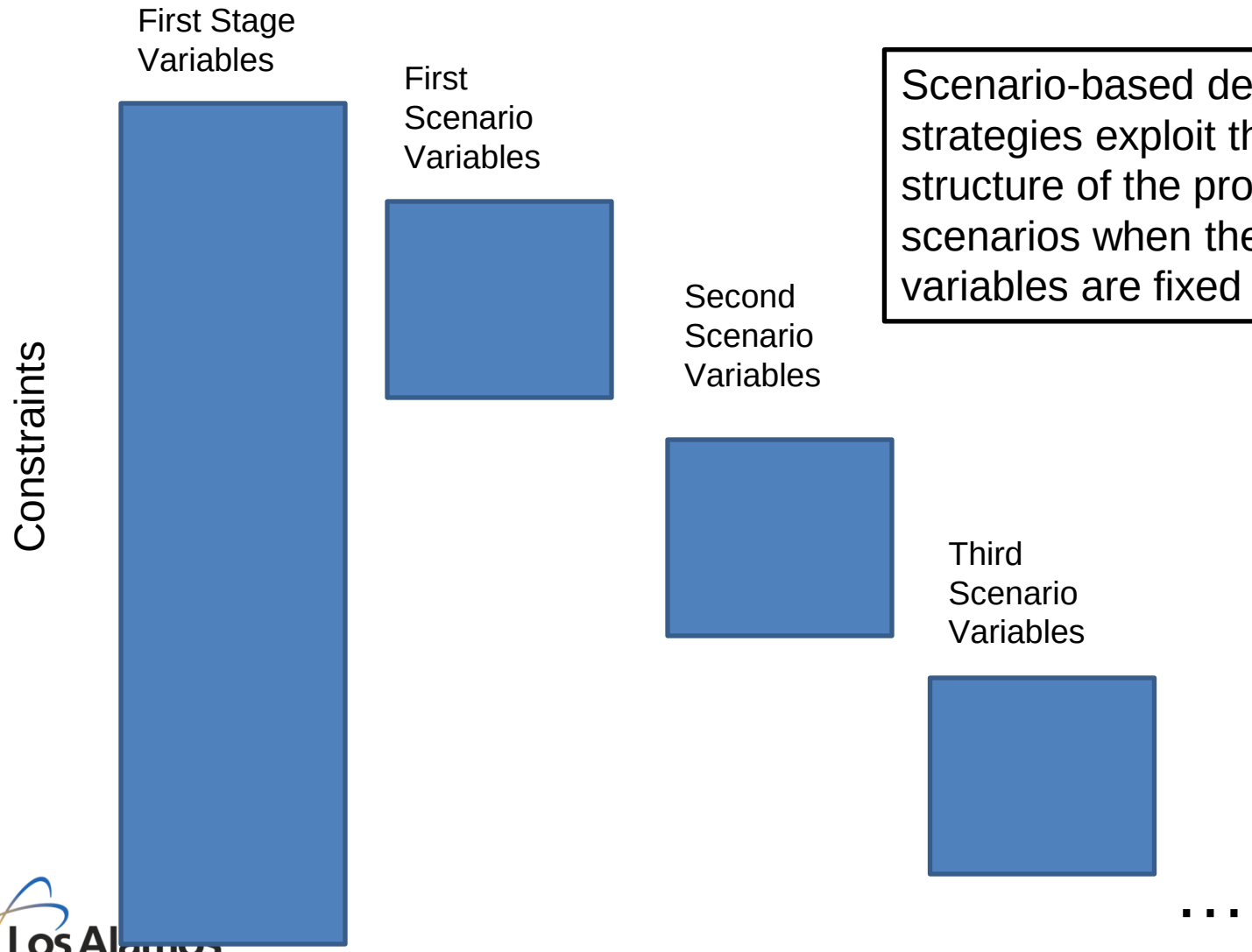
- System objectives
  - Resilience metrics
  - Objective function
    - Budget
    - Robust performance
    - Chance constrained performance
- Upgrade costs



Implementation of "Withstand"—Algorithm

- Baseline Standard
  - CPLEX 12.6—commercial mixed integer program solver
- Decomposition Algorithms (cutting planes)
  - Danzig-Wolfe
  - Benders
  - Disjunctive
  - Logic
  - Scenario ← Biggest computational gains

Implementation of "Withstand"—Decomposition Algorithm



Scenario-based decomposition strategies exploit the separable structure of the problem over scenarios when the first stage variables are fixed

Los Alamos NATIONAL LABORATORY EST. 1943
Operated by Los Alamos National Security, LLC for NNSA

Implementation of "Withstand"—Scenario Based Decomposition

$$ResilientDesign(S)$$

$$s \leftarrow chooseScenario(S)$$

$$\sigma \rightarrow solveMIP(s)$$

$$while\ \left(\sim Feasible(\sigma, S \backslash s)\right)$$

$$s \rightarrow s \cup chooseScenario(S \backslash s)$$

$$\sigma \rightarrow solveMIP(s)$$

Solve over all damage scenarios

Select 1 scenario

Design network for damage scenario 1

Is solution feasible for remaining scenarios

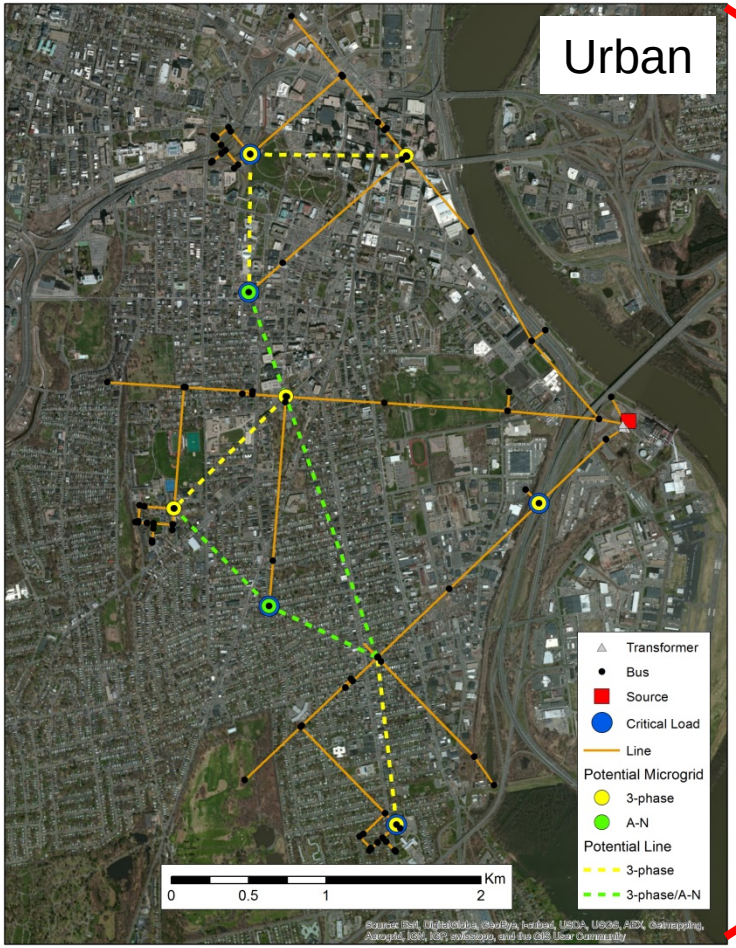
If NOT, add an infeasible scenario to the set under consideration

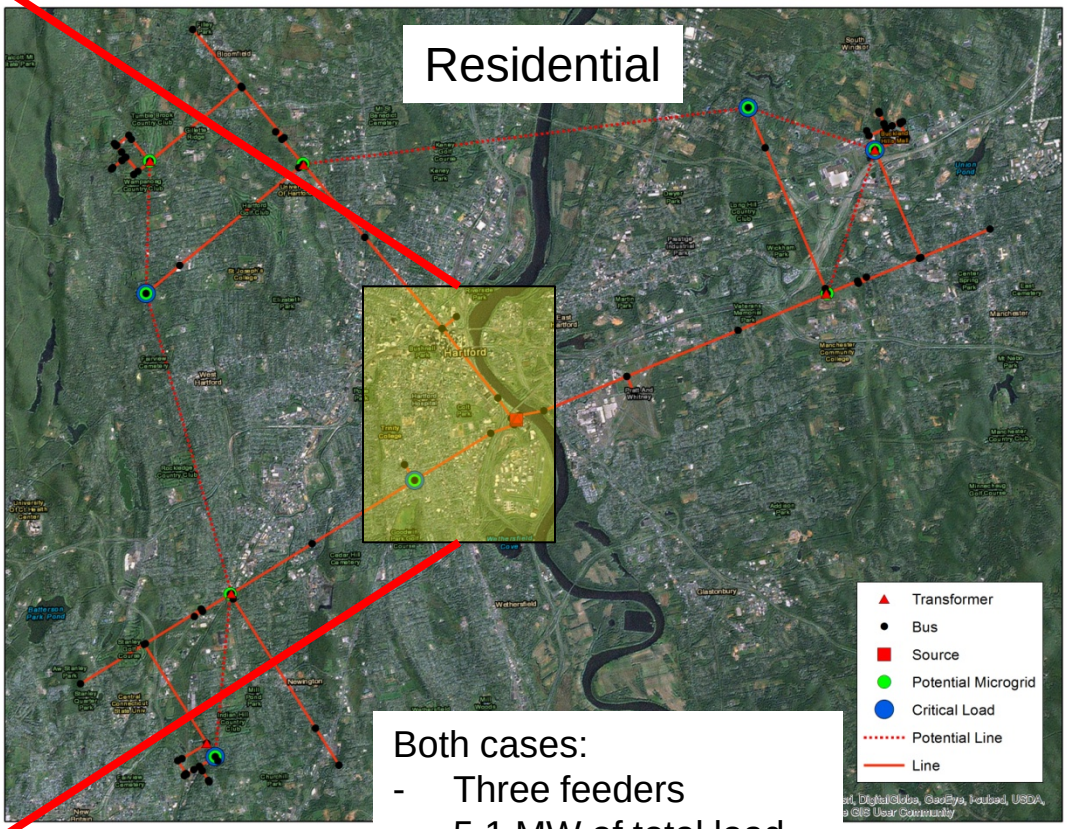
Find a new solution

Iterate until solution is feasible for all scenarios

Implementation of “Withstand”—Snow/Ice/Wind Example

Two base-model configurations—“Dense Urban” and “Sparse Residential”
Range of damage intensity—Light damage to Heavy damage
Different trade off between 1) microgrids 2) new interties 3) hardening
Based on IEEE 34 – Promote openly sharable problem sets





Both cases:
- Three feeders
- 5.1 MW of total load
- 2.1 MW of critical load

Assumptions

Distributed generators provide firm generation, e.g. natural gas CHP

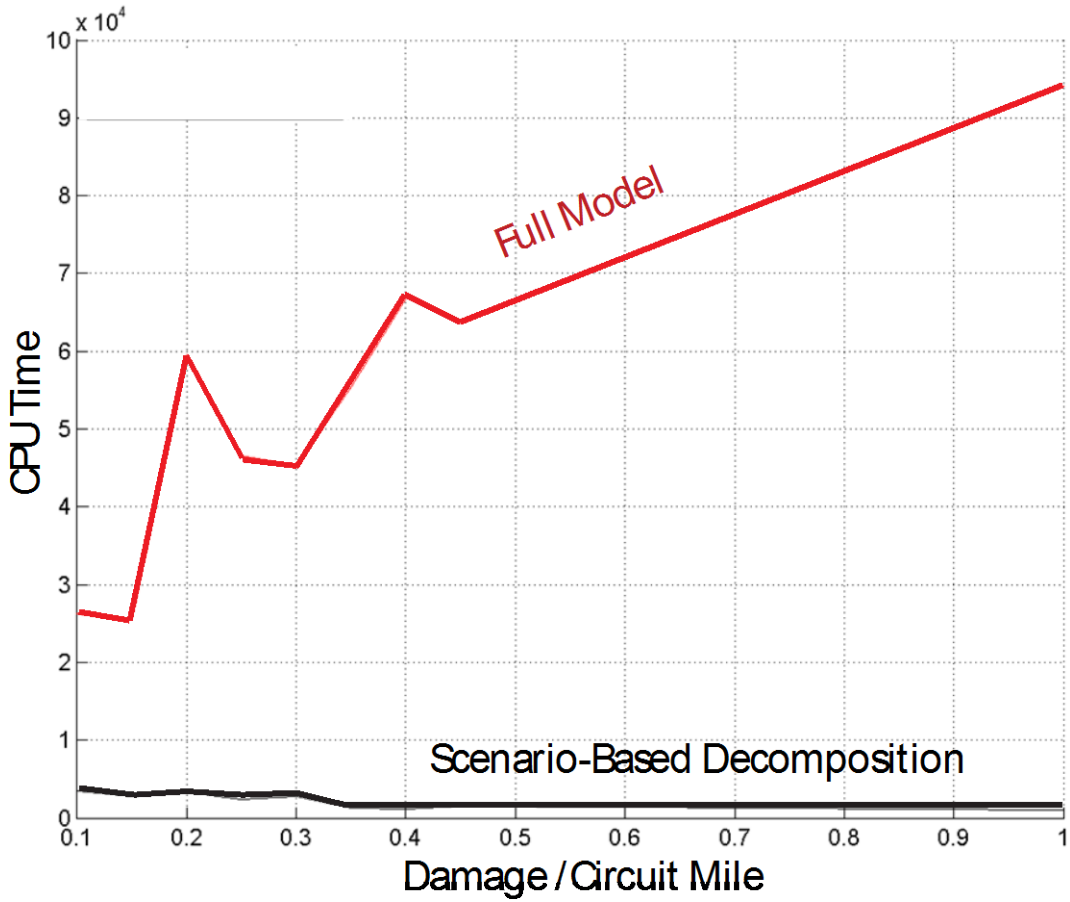
Circuits or sections of circuits configured as trees

Loads and/or generators stay on the phases where they were installed

Costs…… (can be modified based on user specifications)

Device	Type	Cost Range	Suggested cost	Source
$c_{i,j}$	overhead 3-phase	\$60k-\$150k/mile	\$95k/mile	State of
$c_{i,j}$	overhead 1-phase	\$40k-\$75k/mile	\$55k/mile	Virginia Study on
$c_{i,j}$	underground 3-phase	\$40k-\$1,500k/mile	\$500k/mile	Underground Circuits
$c_{i,j}$	underground 1-phase	\$40k-\$1,500k/mile	\$100k/mile	-
$\kappa_{i,j}$	automatic, 3-phase, overhead	–	\$15k	Tom Bialek (SDG&E)
$\kappa_{i,j}$	automatic, 3-phase, underground	–	\$30k	-
$\kappa_{i,j}$	manual, 3-phase, overhead	–	\$7.5k	-
$\kappa_{i,j}$	manual, 3-phase, underground	–	\$20k	-
$\kappa_{i,j}$	automatic, 1-phase, overhead	–	\$10k	-
$\kappa_{i,j}$	automatic, 1-phase, underground	–	\$25k	-
$\kappa_{i,j}$	manual, 1-phase, overhead	–	\$5	-
$\kappa_{i,j}$	manual, 1-phase, underground	–	\$15k	-
$\zeta_{i,j}$	Natural gas CHP variable	–	\$1,500k/MW	EIA 2025 Study
$\zeta_{i,j}$	Natural gas CHP fixed	–	\$500k	

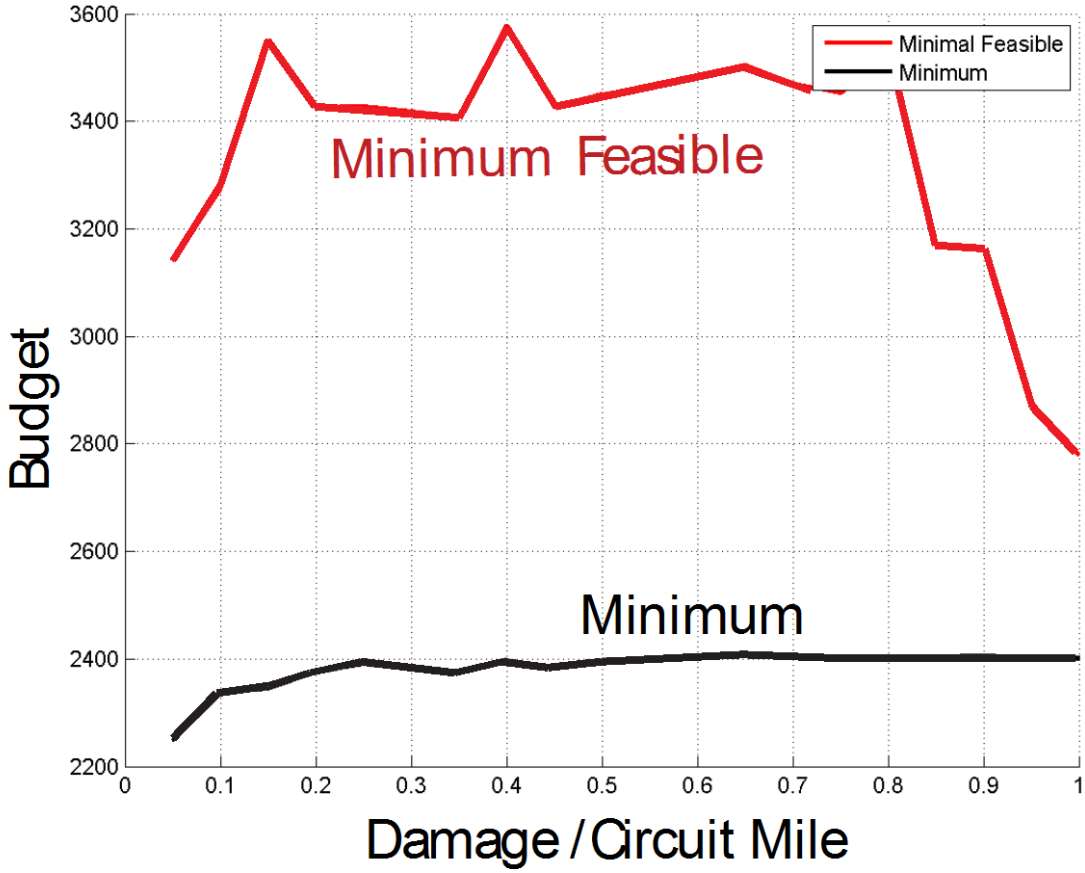
Implementation of "Withstand"—Computational Requirements



Full Model
- Over 90,000 binary variables
- Implemented on "out-of-the-box" CPLEX solver
- CPLEX does not recognize scenario structure

Scenario-Based Decomposition
- 10X speed up

Implementation of "Withstand"—Value of a Multi-Scenario Approach



Multi-scenario approach discovers and leverages synergistic upgrades enabled by network structure

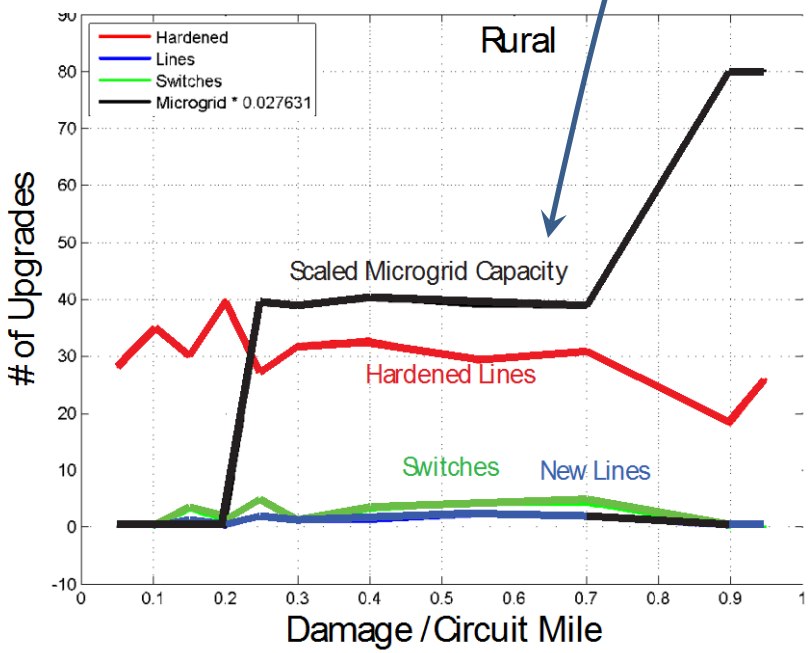
Implementation of "Withstand"—Urban vs Rural Upgrades

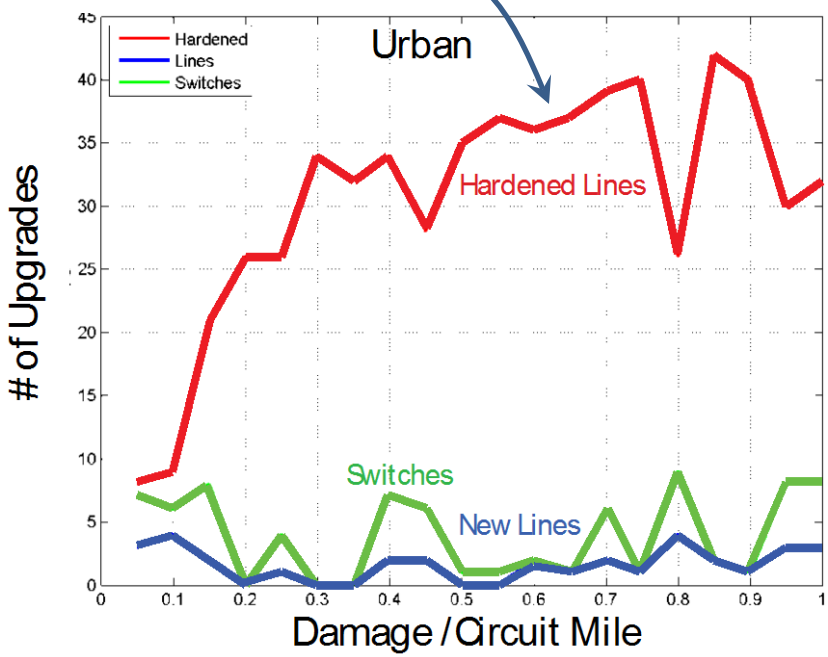
Assumptions

- Ice/Wind/Snow → Uniform damage
- Hardened asset damage rate 1/100 of regular assets

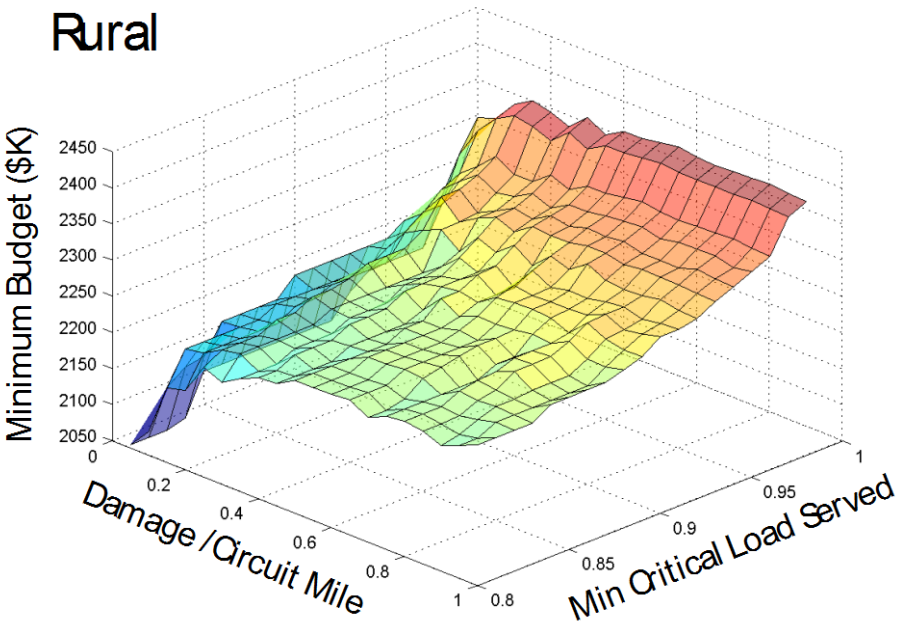
Observations

- Long distances in rural favor microgrids over new lines or asset hardening
- Jumps in microgrid capacity associated with critical load service
- Hardening of existing lines dominates in urban environments



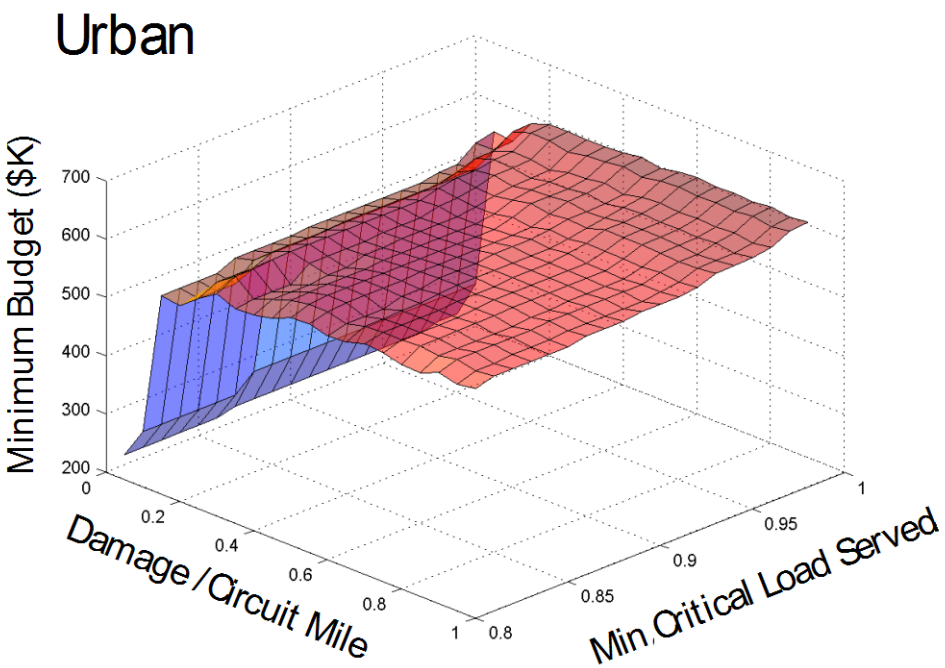


Implementation of "Withstand"—Urban vs Rural Budgets

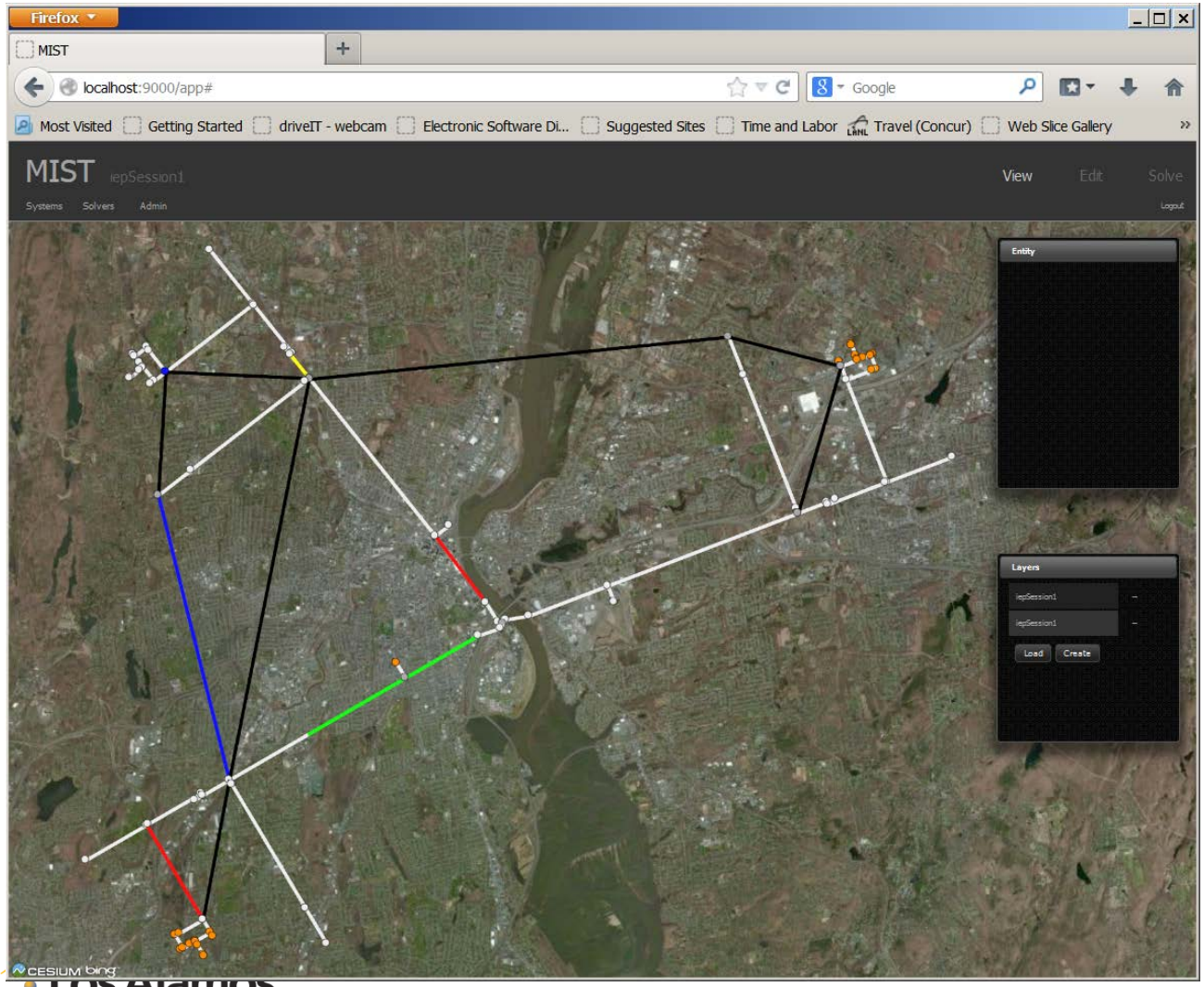


Observations

- Rural networks require larger resilience budgets/MW served
- Both urban and rural budget are insensitive to damage rate beyond a relatively low threshold
- Urban budget is insensitive to critical load requirements

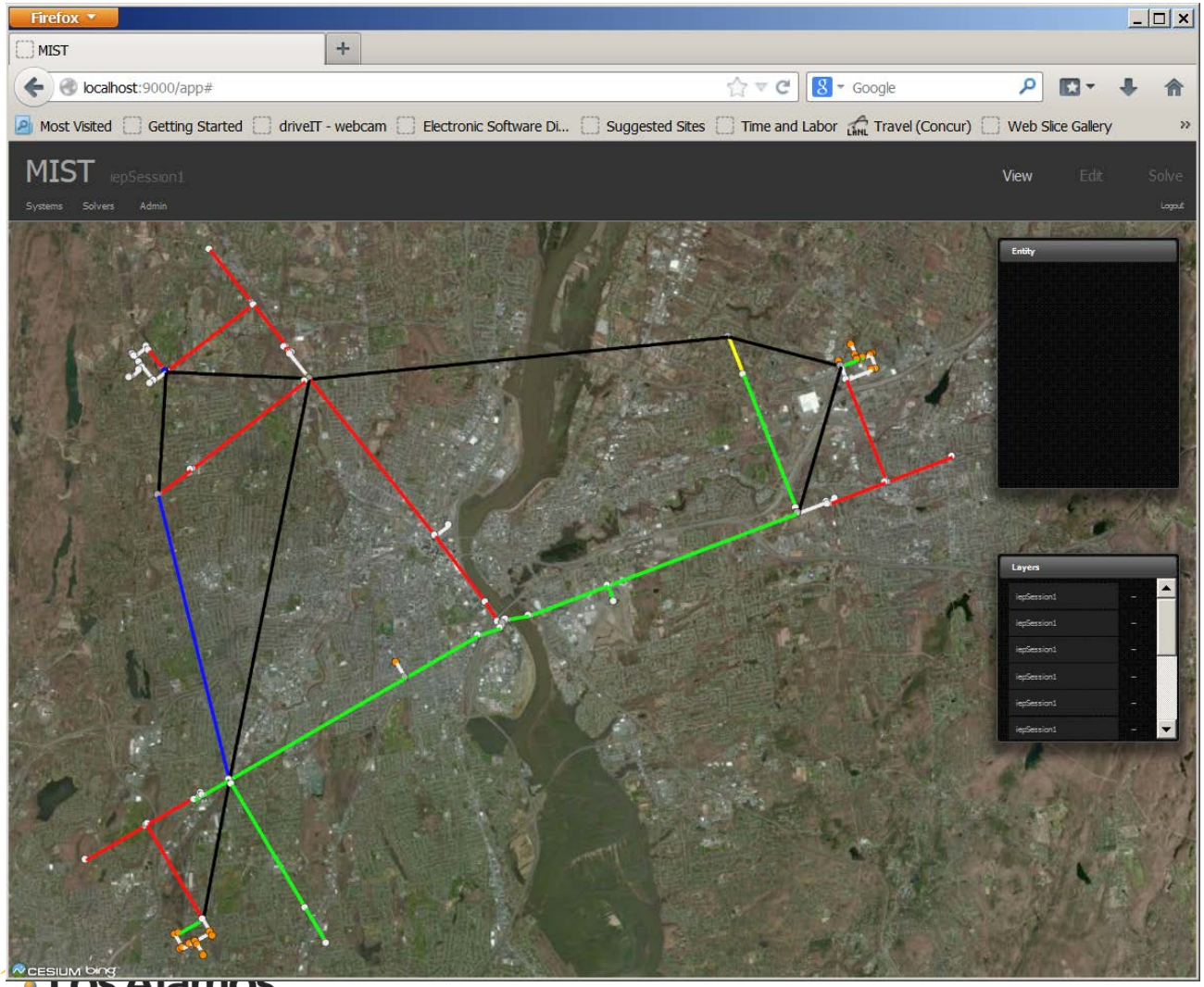


MIST – Rural, 10% Damage



- Critical Load
- Generation
- Damaged Lines
- Hardened Lines
- New Lines
- Unbuilt New Lines
- Switches

MIST – Rural, 100% Damage



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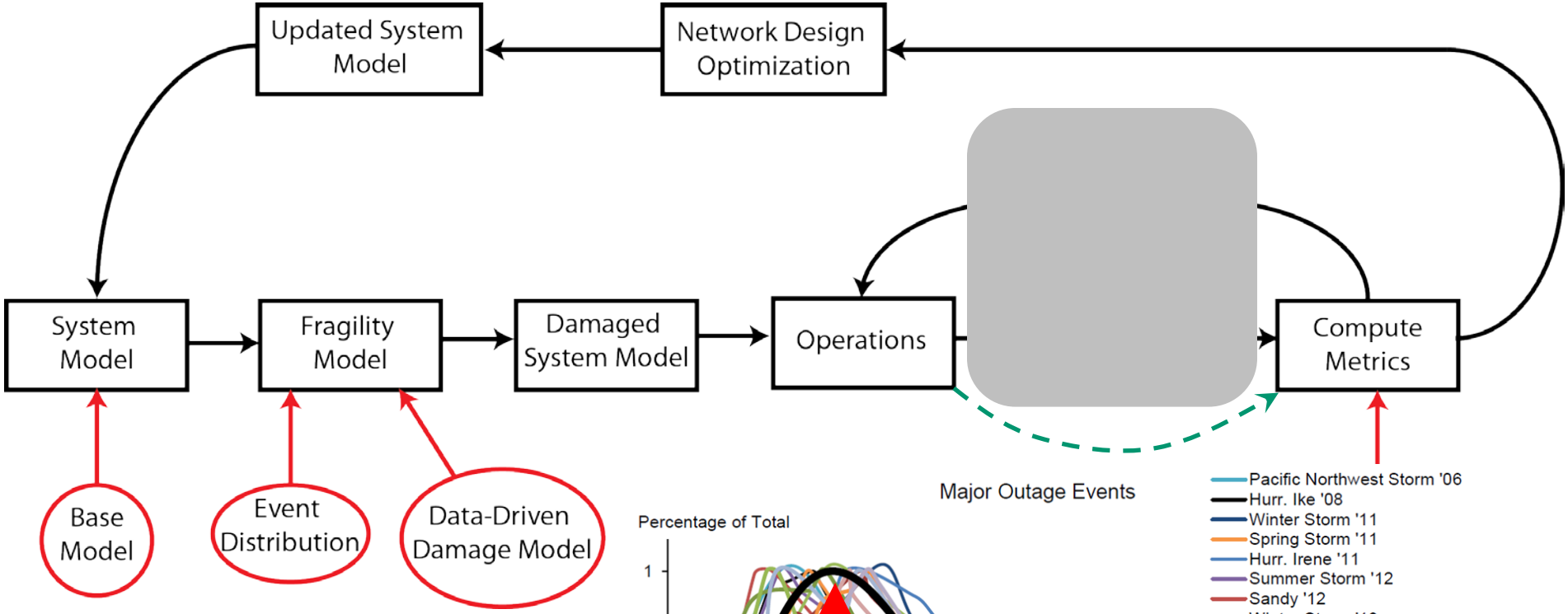
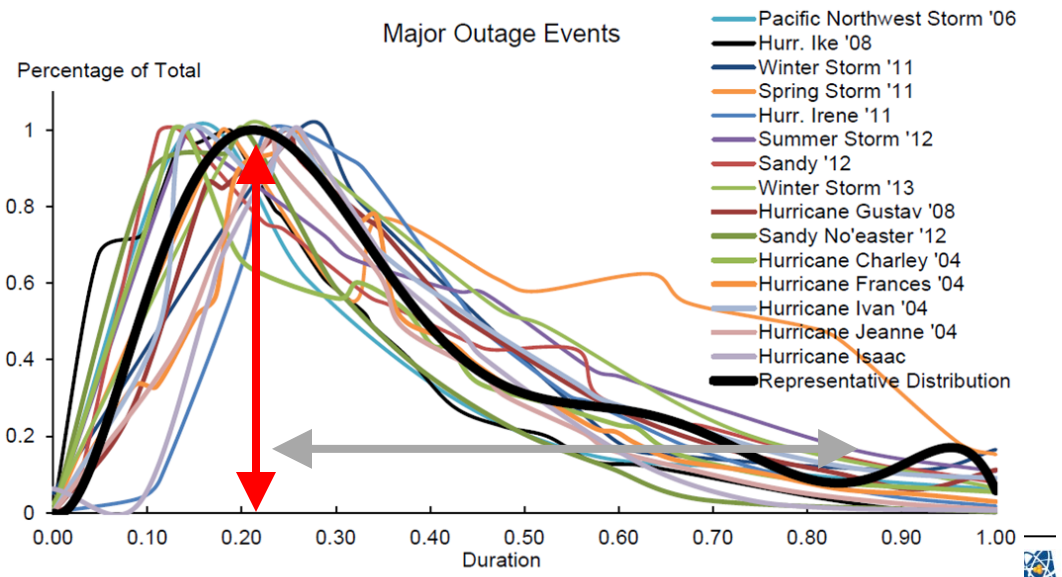
Resilience Design Process Flow—Today's Summary





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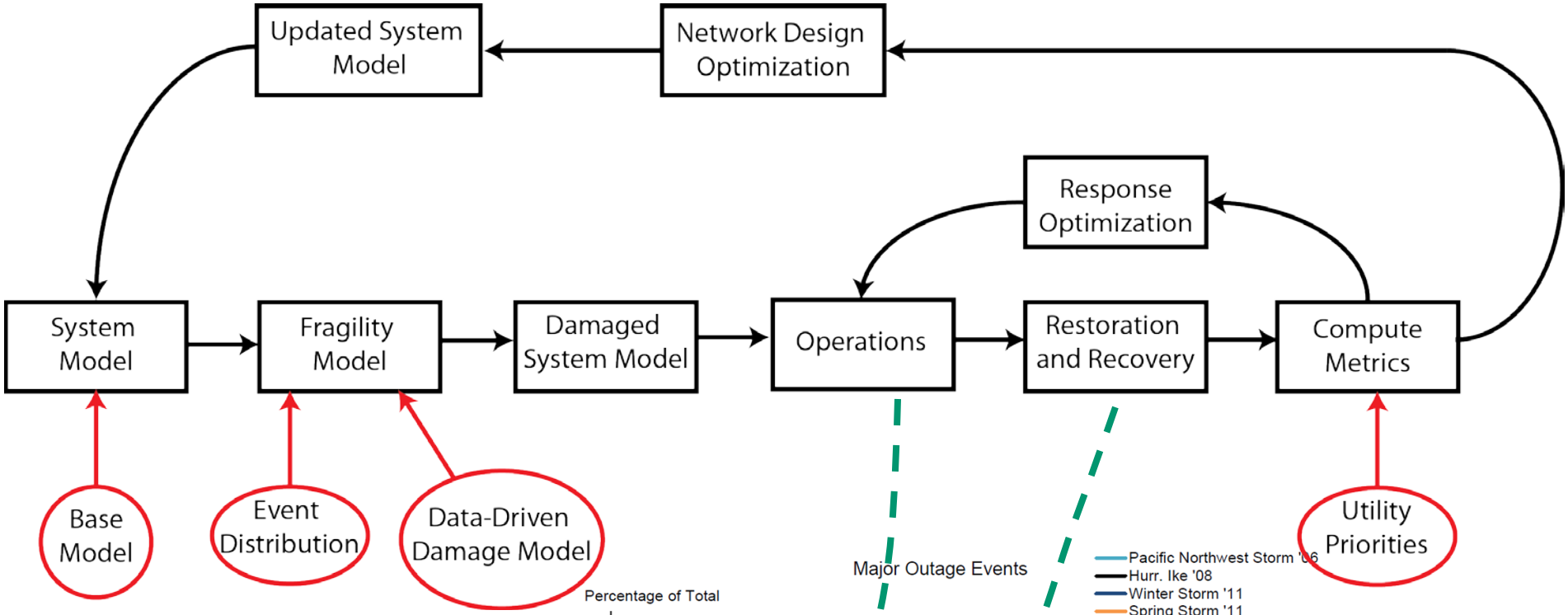
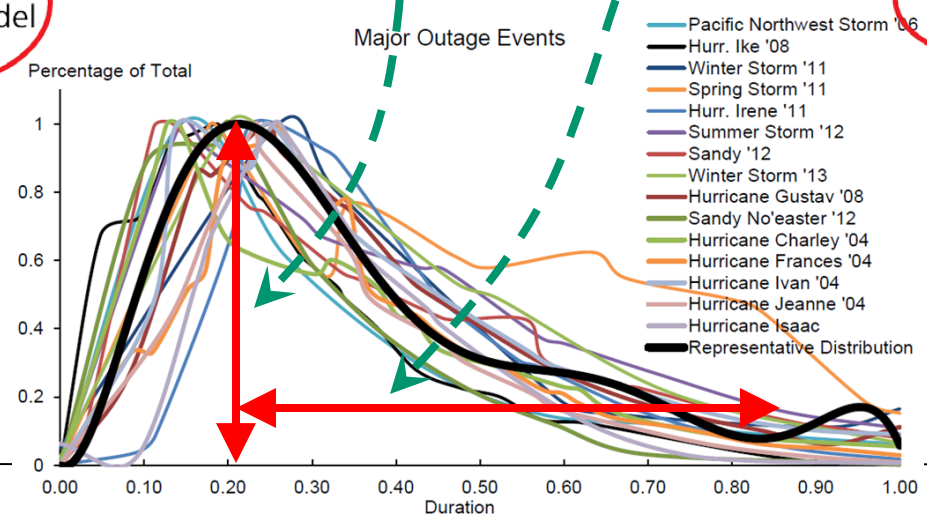
Resilience Design Process Flow—End Goal Reminder





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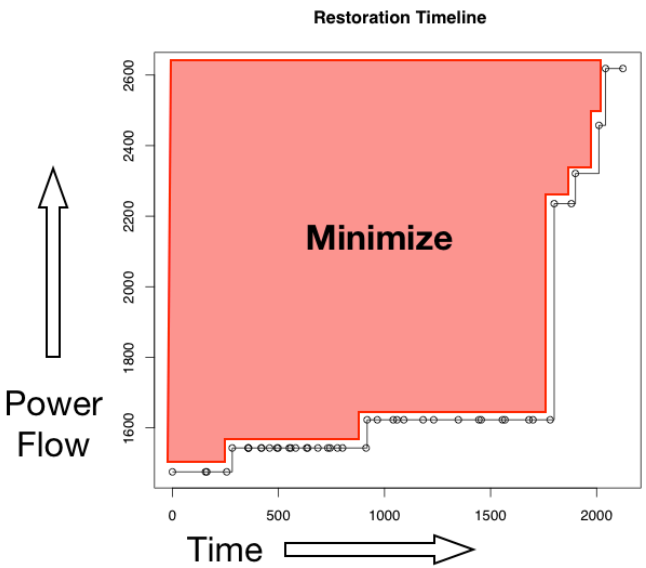
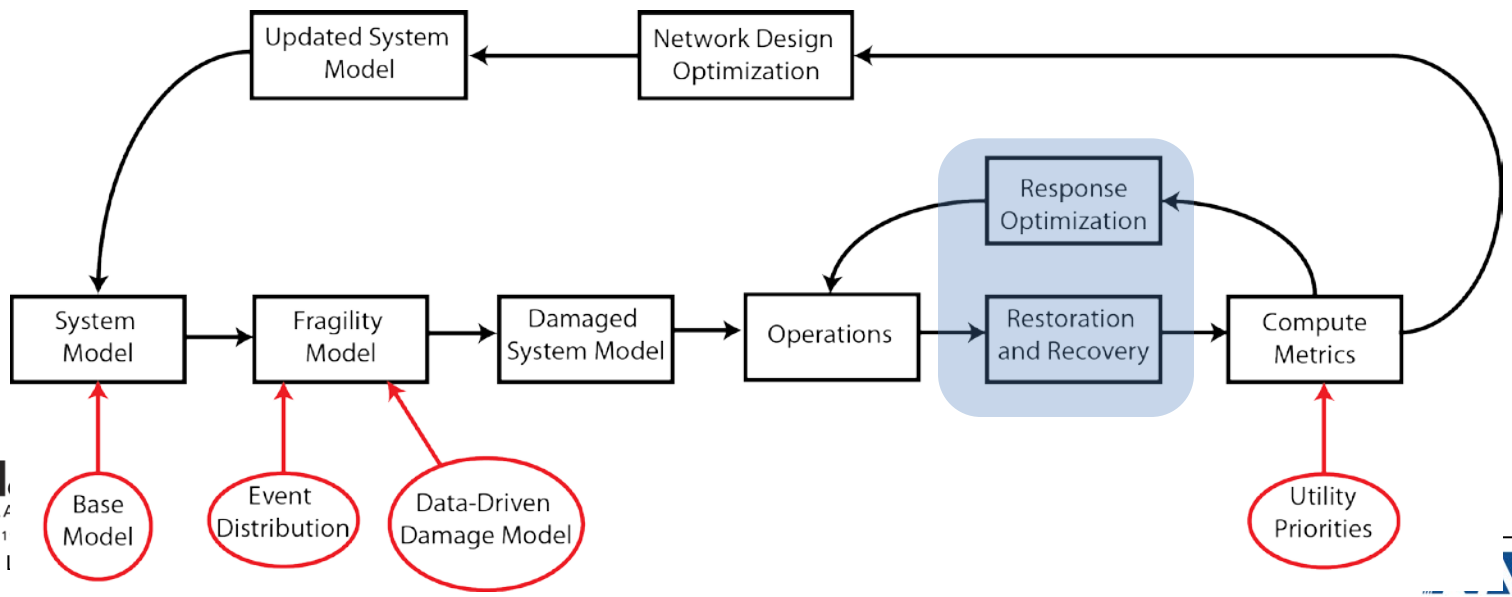
Resilience Design Process Flow—Restoration



Example: Minimize the size and duration of a black out.

Combine grid operation requirements (restore power as quickly as possible) with transportation requirements (routing crews on a potentially damaged road network)

P. van Hentenryck, C. Coffrin, and R. Bent *Vehicle Routing for the Last Mile of Power System Restoration*. 17th Power Systems Computation Conference (PSCC 2011), August 2011, Stockholm, Sweden



Steps Toward the End Goal

- **Include restoration process and optimization**
- Include voltage and reactive power
  - Current: Defer to an external power flow solver to check voltage and reactive power constraints – “no good” cuts
  - End Goal: Improve computationally efficiency by adding these details to underlying optimization module
- More flexible resilience metrics
  - Current: Post-event performance criteria modeled as hard constraints
  - End Goal: 1) Extend to chance constraints and 2) Put performance in the objective

Beyond the End Goal—Resiliency Tool Suite

Presidential Policy Directive - Critical Infrastructure Security and Resilience

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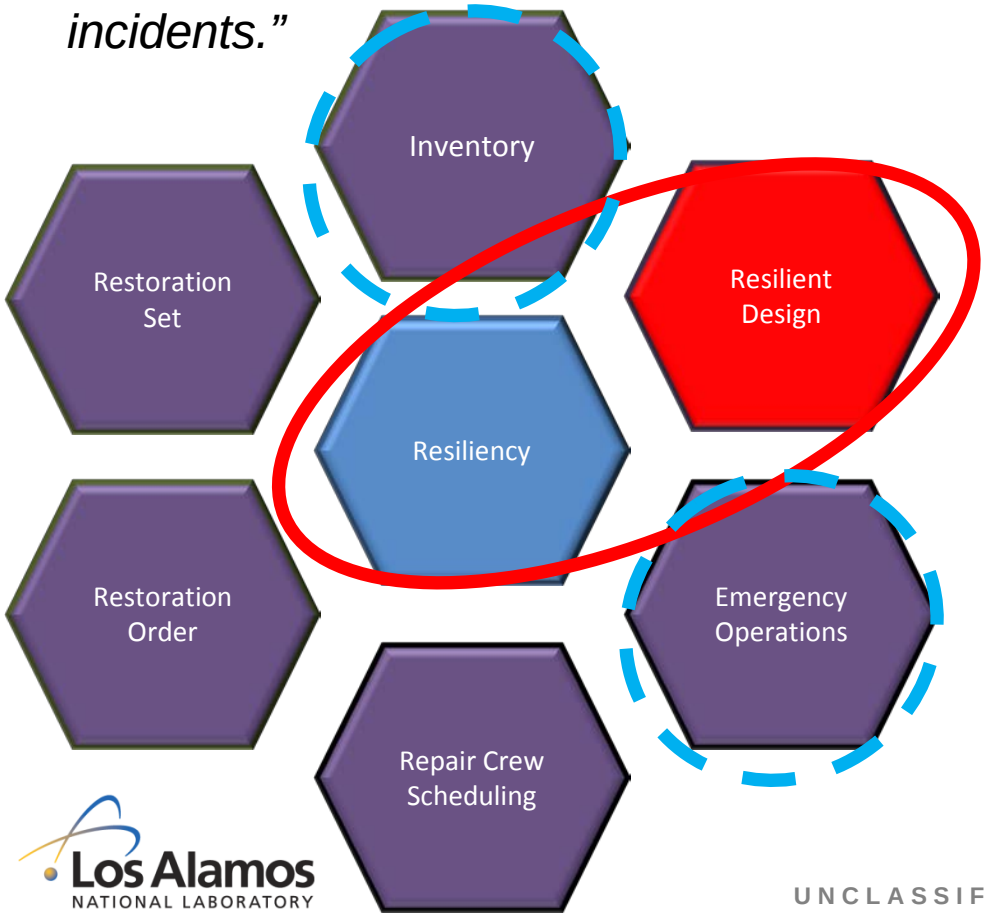

Decision support tool for critical infrastructure disaster planning and response, composed of interconnected modules

Today—Resilient deign to **withstand** initial blow

End Goal— + System restoration to capture **recovery** from initial blow

Beyond the End Goal— + Inventory and Emergency operation to **prepare** for events

Conclusions and Future Work

- Resilience studies with partner utilities
  - Better understanding of stakeholder needs
  - Validate and improve approach
  - Disseminate results and technology

- Data needs
  - System-level data—suitable for a power flow solver
  - Geo-locations
  - Data on historical events
  - Damaged components, repair times, repair crews

- Extensions
  - Robust network design
  - Software connections to additional commercial/open source power system software packages
  - Incorporation of restoration models/optimization
  - Real-time systems

References

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E. Lawrence, R. Bent, S. vander Wiel. *Model Bank State Estimation for Power Grid Using Importance Sampling*, Technometrics, 2013.

R. Bent, G. L. Toole, and A. Berscheid. *Transmission Network Expansion Planning with Complex Power Flow Models,* IEEE Transactions on Power Systems, Volume 27 (2): 904-912, 2012.

E. Yamangil, R. Bent, S. Backhaus. Optimal Resilient Distribution Grid Design Under Stochastic Events, under review

Assumptions

Distributed generators provide firm generation, e.g. natural gas CHP

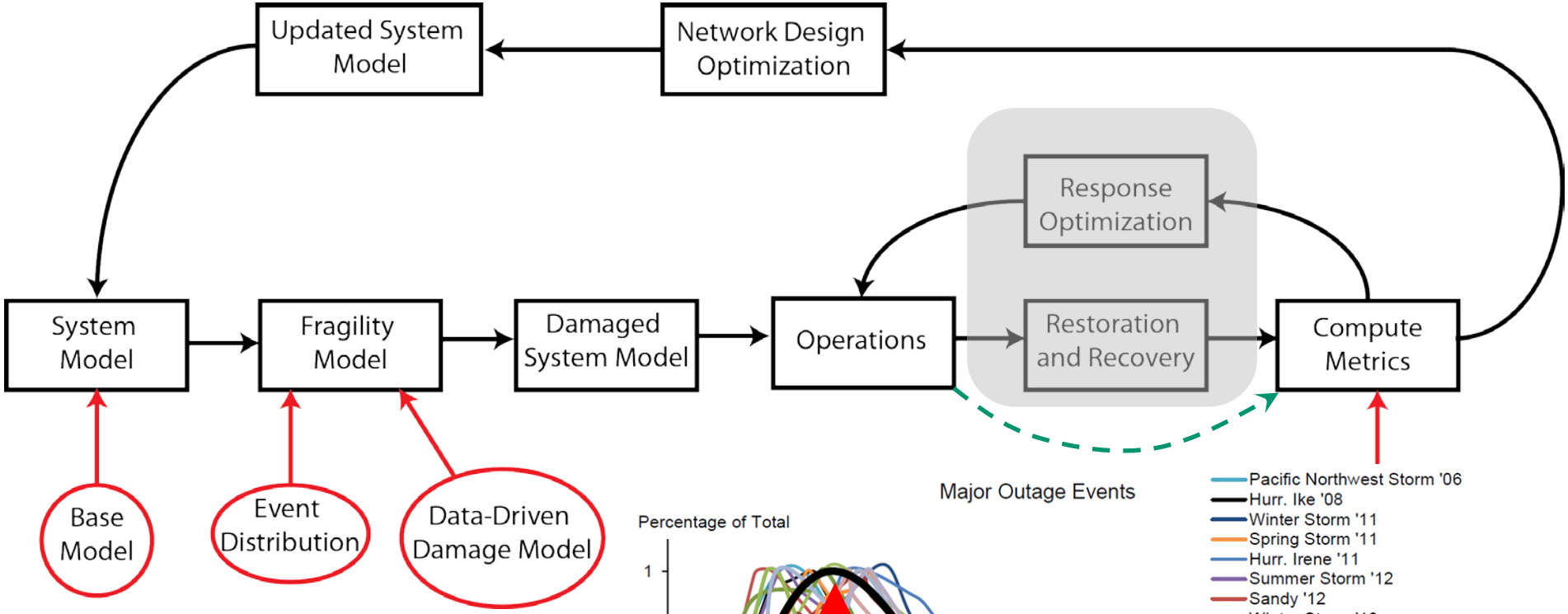
Circuits or sections of circuits configured as trees

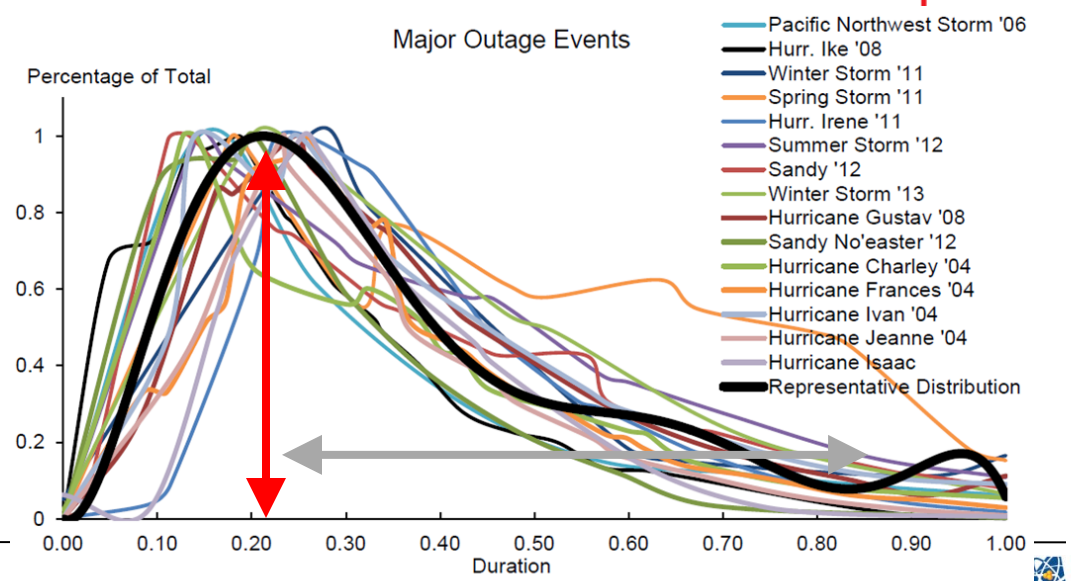
Loads and/or generators stay on the phases where they were installed

Costs…… (can be modified based on user specifications)

Device	Type	Cost Range	Suggested cost	Source
$c_{i,j}$	overhead 3-phase	\$60k-\$150k/mile	\$95k/mile	State of
$c_{i,j}$	overhead 1-phase	\$40k-\$75k/mile	\$55k/mile	Virginia Study on
$c_{i,j}$	underground 3-phase	\$40k-\$1,500k/mile	\$500k/mile	Underground Circuits
$c_{i,j}$	underground 1-phase	\$40k-\$1,500k/mile	\$100k/mile	-
$\kappa_{i,j}$	automatic, 3-phase, overhead	–	\$15k	Tom Bialek (SDG&E)
$\kappa_{i,j}$	automatic, 3-phase, underground	–	\$30k	-
$\kappa_{i,j}$	manual, 3-phase, overhead	–	\$7.5k	-
$\kappa_{i,j}$	manual, 3-phase, underground	–	\$20k	-
$\kappa_{i,j}$	automatic, 1-phase, overhead	–	\$10k	-
$\kappa_{i,j}$	automatic, 1-phase, underground	–	\$25k	-
$\kappa_{i,j}$	manual, 1-phase, overhead	–	\$5	-
$\kappa_{i,j}$	manual, 1-phase, underground	–	\$15k	-
$\zeta_{i,j}$	Natural gas CHP variable	–	\$1,500k/MW	EIA 2025 Study
$\zeta_{i,j}$	Natural gas CHP fixed	–	\$500k	

Restoration Optimization: A brief note





Source: Department of Energy, Office of Electrcity Delivery and Energy Reliability

Restoration Optimization

- 3-step approach
  - Identify the minimum set of components to repair
    - MIP (small instances) or LNS over linearized model
  - Identify an order of restoration
    - LNS over linearized model
  - Assign repairs to crews and route them through a potentially damaged/obstructed road network
    - Decomposition over LNS over CP

Restoration Set

- Finding a smallest set of items to restore to obtain full grid capacity
- Challenging for MIP solvers
- LNS (local search) over the MIP model

Inputs:

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

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

Minimize

$$\sum_{i \in N \cup L} y_i \tag{1}$$

Subject to:

$$\sum_{b \in N^b} \sum_{i \in N_b^l} P_i^v = MaxFlow \tag{2}$$

$$y_i = 1 \quad \forall i \in N \setminus D \tag{3}$$

Constraints (4–11) from Figure 1

Restoration Ordering Model

Inputs:

$\mathcal{PN} = \langle N, L \rangle$	the power network
D	the set of damaged items
R	the set of items to repair
$MaxFlow$	the maximum flow

Variables:

$flow_k$	- the flow in step k
$r_{i,k} \in \{0,1\}$	- item i is repaired in step k
$y_{i,k} \in \{0,1\}$	- item i is activated in step k
$z_{ik} \in \{0,1\}$	- item i is operational in step k
$P^l_{ik} \in (-\hat{P}^l_i, \hat{P}^l_i)$	- power flow on line i in step k
$P^v_{ik} \in (0, \hat{P}^v_i)$	- power flow on node i in step k
$\theta_{ik} \in (-\frac{\pi}{6}, \frac{\pi}{6})$	- phase angle on bus i in step k

Minimize

$$\sum_{k=1}^{|R|} (MaxFlow - flow_k) \quad (1)$$

Subject to: $(1 \leq k \leq |R|)$

$$flow_k = \sum_{b \in N^b} \sum_{i \in N^l_b} P^v_{ik} \quad (2)$$

$$\sum_{r \in R} o_{rk} = k \quad (3)$$

$$o_{rk-1} \leq o_{rk} \quad \forall r \in R \quad (4)$$

$$y_{ik} \leq o_{ik} \quad \forall i \in D \quad (5)$$

$$y_{ik} = 1 \quad \forall i \in (N \cup L) \setminus D \quad (6)$$

$$y_{ik} = 0 \quad \forall i \in D \setminus R \quad (7)$$

$$z_{ik} = y_{ik} \quad \forall i \in N^b \quad (8)$$

$$z_{ik} = y_{ik} \wedge y_{jk} \quad \forall j \in N^b, \forall i \in N^g_j \cup N^l_j \quad (9)$$

$$z_{ik} = y_{ik} \wedge y_{L^+_i k} \wedge y_{L^-_i k} \quad \forall i \in L \quad (10)$$

$$\sum_{j \in N^l_i} P^v_{jk} = \sum_{j \in N^g_i} P^v_{jk} + \sum_{j \in LI_i} P^l_{jk} - \sum_{j \in LO_i} P^l_{jk} \quad \forall i \in N^b$$

$$0 \leq P^v_{ik} \leq \hat{P}^v_i * z_{ik} \quad \forall j \in N^b, \forall i \in N^g_j \cup N^l_j \quad (11)$$

$$-\hat{P}^l_i * z_{ik} \leq P^l_i \leq \hat{P}^l_i * z_{ik} \quad \forall i \in L \quad (12)$$

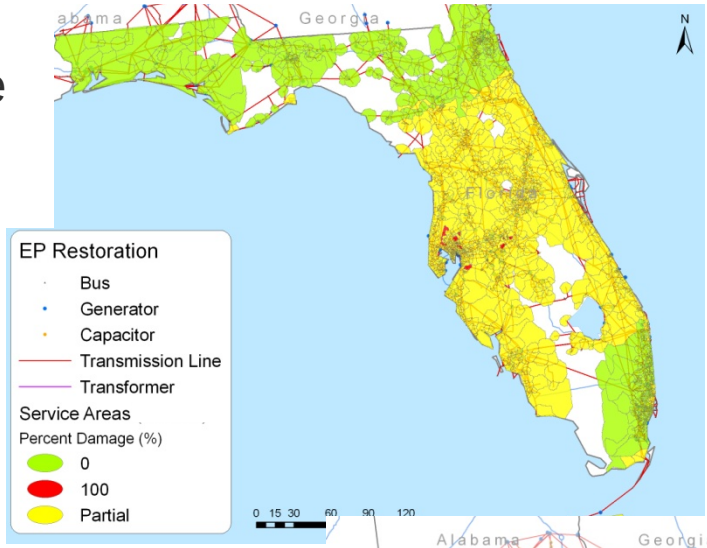
$$P^l_{ik} \geq B_i * (\theta_{L^+_i k} - \theta_{L^-_i k}) + M * (\neg z_{ik}) \quad \forall i \in L \quad (13)$$

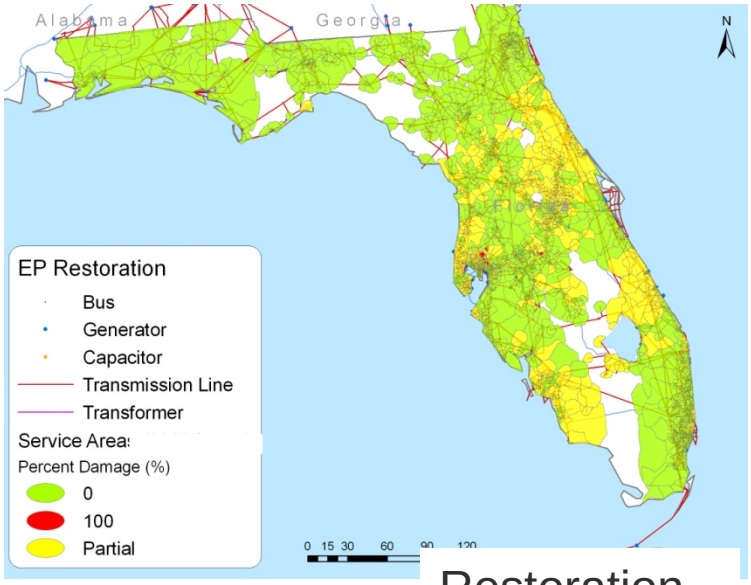
$$P^l_{ik} \leq B_i * (\theta_{L^+_i k} - \theta_{L^-_i k}) - M * (\neg z_{ik}) \quad \forall i \in L \quad (14)$$

- MIP is intractable even for small transmission networks
- LNS over the MIP Model

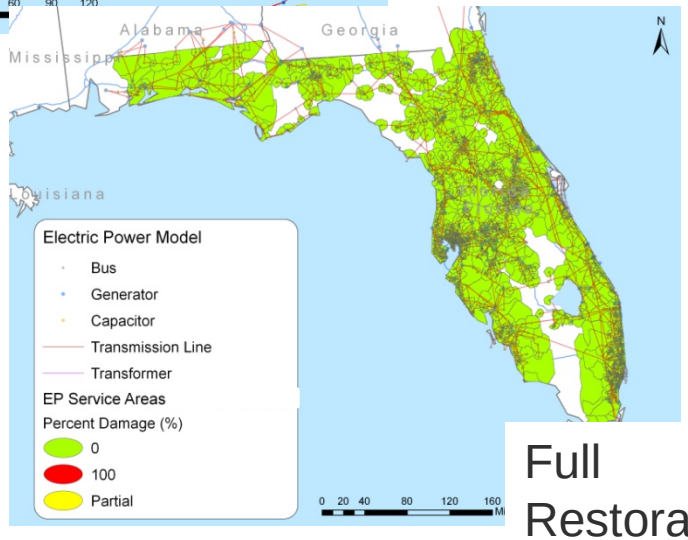
Restoration Progression

Initial Outage Area





Restoration After 2 Weeks



Full Restoration

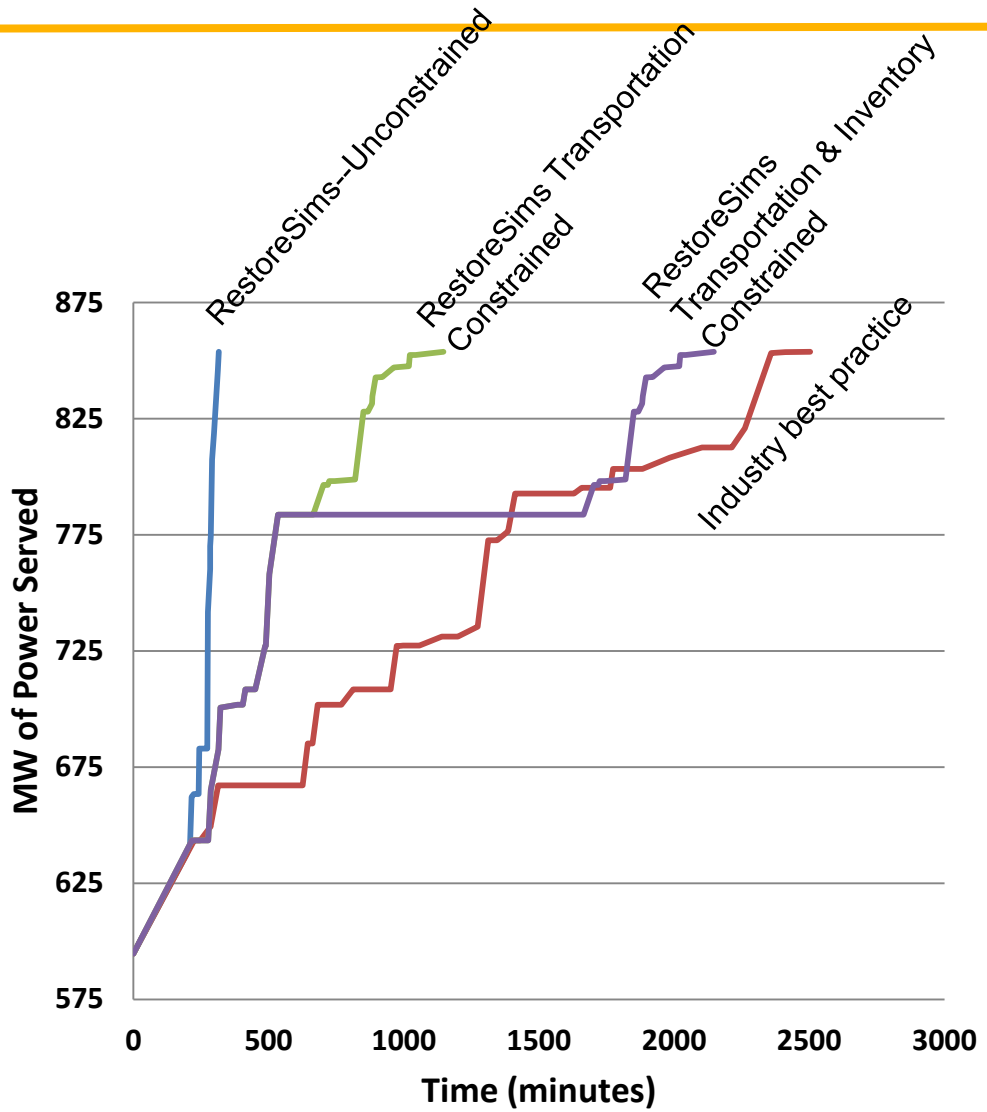
Restoration Optimization

Current State of Practice

- RestoreSims integrates:
  - Grid, Gas
  - Transportation, Crew scheduling
  - Repair component inventory
  - Repair component warehousing
- Reveals impact of transportation and inventory constraints on restoration
- Enables utilities to design
  - Repair component inventory
  - Component warehousing
- Capability outperforms utilization based restoration practice, e.g. prioritizing based on pre-event utilization

Planned R&D

- Adapt to distribution grid models
- Convert to an operational tool



Restoration Progression on 67 Asset Repair Scenario