LANL Grid Science Winter School and Conference—Held in January 2015—Next Event January 2017

New <u>interdisciplinary</u> R&D community for modernized infrastructure

<u>2015 Grid Science Winter School and Conference</u>
Physics, Control, Optimization, Computer Science, Statistics, Operations Research, Power Engineering

<u>Students From</u>: Columbia, Rutgers, MIT, CalTech, ETH Zurich, UC Berkeley, UCSD, UCSB, UTexas, UVermont, UMinnesota, UMichigan, UWashington, UConn, NICTA Australia, Skolkovo Tech, LANL

<u>Lecturers</u>: I. Hiskens, UMichigan;
A. Conejo, OSU; **F. Dorfler**, ETH Zurich
M. Chertkov, LANL; D. Bienstock, Columbia
S. Low, Cal Tech; P. van Hentenryck, NICTA Australia
K. Turitsyn, MIT; D. Callaway, UC Berkeley

"The uniqueness of this workshop is inarguable"

"I've never learnt that much in such a short time!"

"Great opportunity for interdisciplinary contact and collaboration"

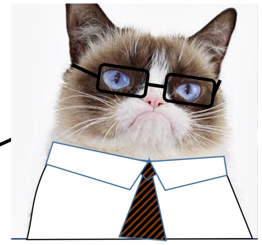
"I learnt a lot of things from the school and will apply those right away in the coming weeks"

LANL Infrastructure Science Team: Integrated at the Program Level

advanced network science initiative (ansi)

Russell Bent (A Division)

Operations Research, Discrete and Continuous Optimization, Heuristics Design, Stochastic/Robust Network Design, Infrastructure Expansion, Resilient Design



Scott Backhaus
DOE and DHS Program Management

Aric Hagberg
ANSI Lead

Michael Chertkov (T Division)

Mathematical Physics, Statistical Physics, Applied Probability, Machine Learning, Graphical Models, Network Design, Stochastic Networks and Dynamics, Optimization

New Scientific Staff

Harsha Nagarajan

Carleton Coffrin

Critical Infrastructure Analysis Team

J. Ambrosiano	R. Boero	M. Ewers	S. Linger
J. Arnold	C. Coffrin	D. Frank	D. Pasqualini
A. Barnes	T. Crawford	L. Inkret	M. Rivera
R. Bent	B. Edwards	H. Khalsa	R. Roberts
			B. Tasseff

New Scientific Staff

Anatoly Zlotnik

Sidhant Misra

Marc Vuffray

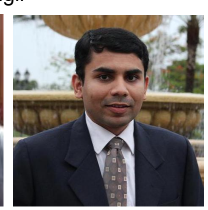
Current/Recent Postdocs and Students

Kaarthik Sundar

Conrado Borraz-Sanchez

Emre Yamangil

Sreenath Madathil



Mowen Lu

Current Postdocs

Line Roald

Andrey Lokhov

Deep Deka

Se-Young Yun

Resilient Infrastructure—Modeling, Analysis, and Design

Los Alamos National Laboratory

Scott Backhaus

Manager for DOE Office of Electricity and DHS Critical Infrastructure Programs

Modeling and Analysis For Extreme Event Resilience—Basic Concepts—Worst Case Versus Risk Assessment

1. Description of events of concern

- Physics model of event
- Probability of event occurrence
- Coupling to infrastructures

2. Assess quantitative impact on

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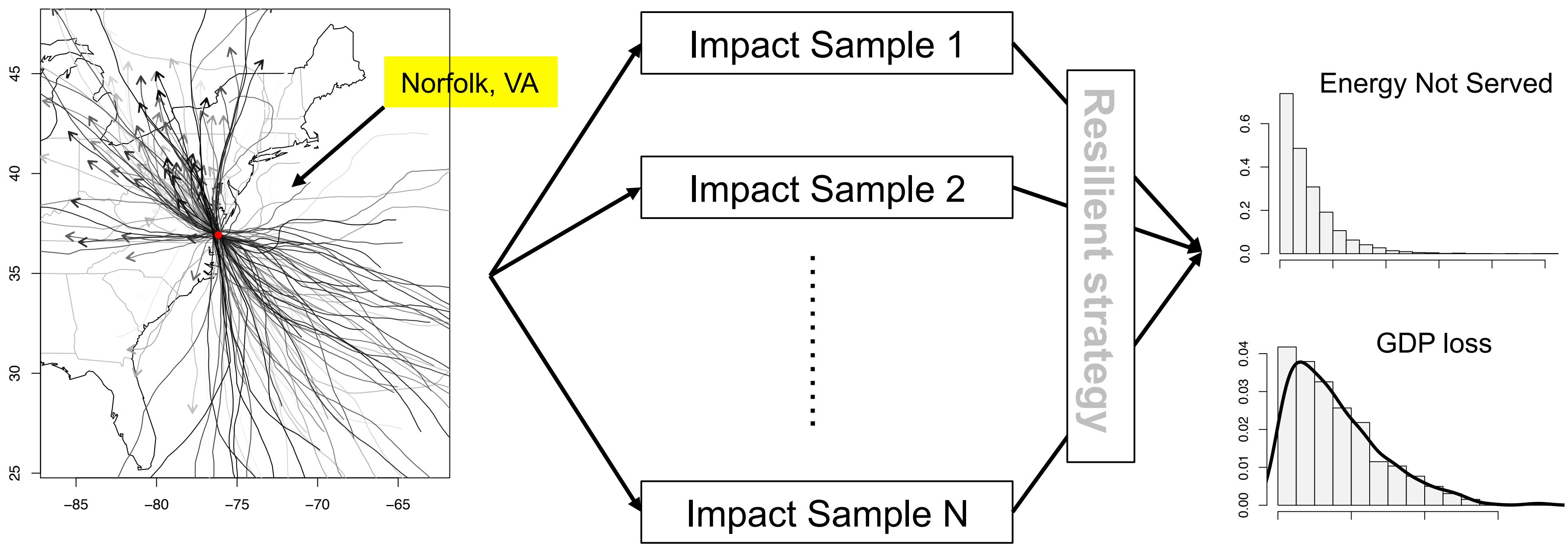
Modeling and Analysis For Extreme Event Resilience—Basic Concepts—Probabilistic Risk Assessment (PRA)

Sample Events
Generate historically-consistent ensemble of 1000's of hurricanes

Evaluate Impacts
Simulate consequences of each hurricane sample—e.g. electric power outage locations and durations

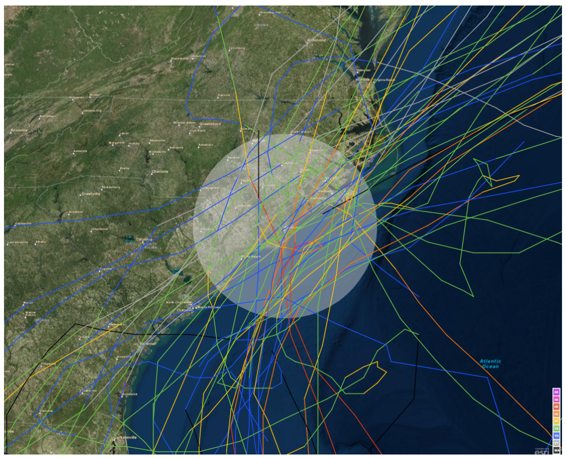
Compute Metrics
Aggregate results to evaluate risk—probability distributions over consequences



Evaluate for base case and for resilient strategy to assess benefits

Modeling and Analysis For Extreme Event Resilience—Event Distribution—Probabilistic Risk Assessment (PRA)

<u>Sparse historical record</u> → <u>Statistical distribution over hurricane parameters</u> → <u>Historically-consistent hurricane ensemble</u>



Landfall distance and heading

$$\lambda(\theta) = \frac{1}{T} \sum_{\substack{i \\ \text{(all storms)}}} k(d_i) k(\theta_i - \theta)$$

Central pressure deficit...<u>Weibull</u>

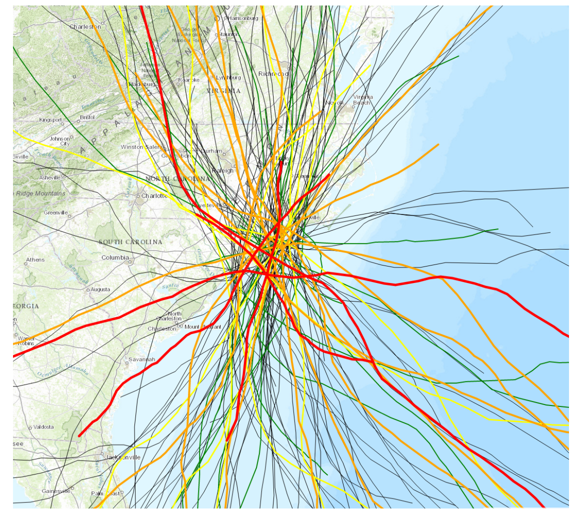
$$P[\Delta P > x] = \exp[-(x/u)^k + (\Delta P_0 / u)^k]$$

Radius of maximum winds and

Forward speed… <u>lognormal</u>

$$\mathcal{N}(\ln x; \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(\ln x - \mu)^2}{2\sigma^2}\right]$$

Each of these independent distributions is fit to the historical data



Input to hurricane probabilistic risk analysis (PRA)

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Electric Power Fragility Models—Existing/Historical Coarse-Grained Models

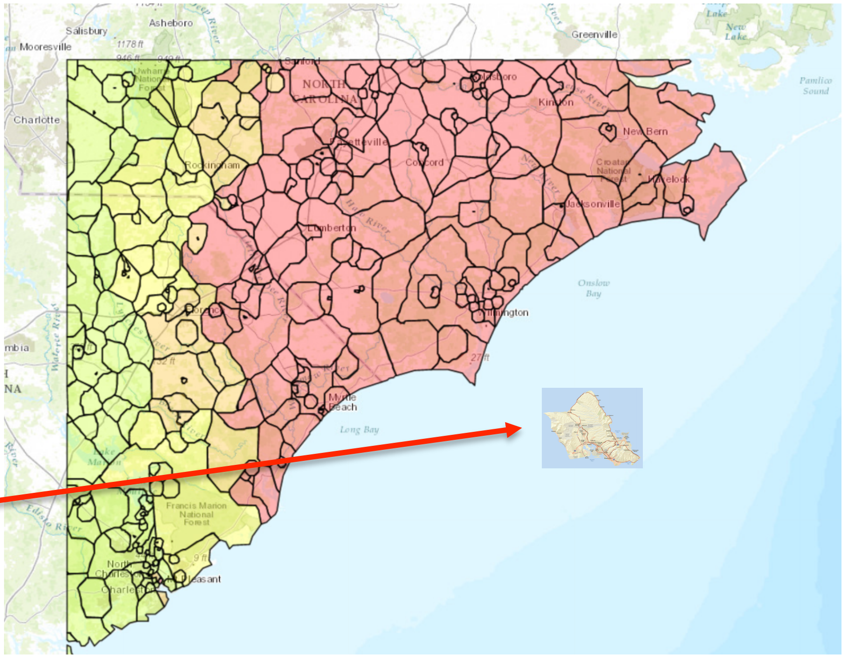
Damage model is a statistical correlation between the maximum sustained wind speed and the number of customer accounts without power

Source data does not differentiate between
- Wind damage to poles and wires
- Inundation damage to transformers/substations

Not extensible to other hazard fields, e.g. peak ground acceleration

Applied at the substation service area resolution

Does not resolve electrical distribution network
- **Cannot resolve:**
  - Correlations in system resilience/hardening
  - Facility locations
  - Engineered properties of the network, e.g. system protection



Modeling and Analysis For Extreme Event Resilience—Principled Path to Coarse-Grained Models

Naïve averaging over important underlying correlations induces <u>systematic</u> errors into coarse-grained models

Systematic errors appear at a scale below the coarse-grain model resolution:

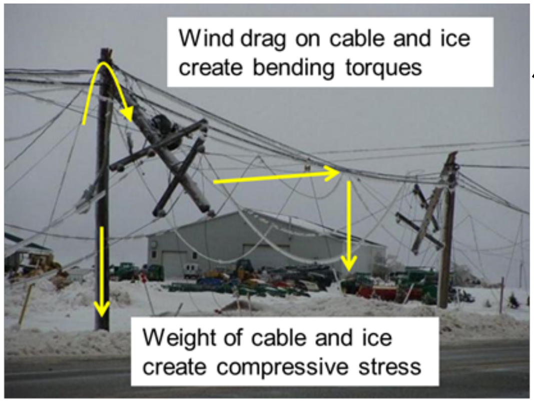
- Circuit-level
- Facility-level

Systematic errors preclude accurate predictive simulation on the coarse-grain scales

<u>Damage and restoration modeling should be done at same (or finer) scale as the correlations…then used to create coarse-grained models</u>

Hurricane Iniki
1992 Kauai

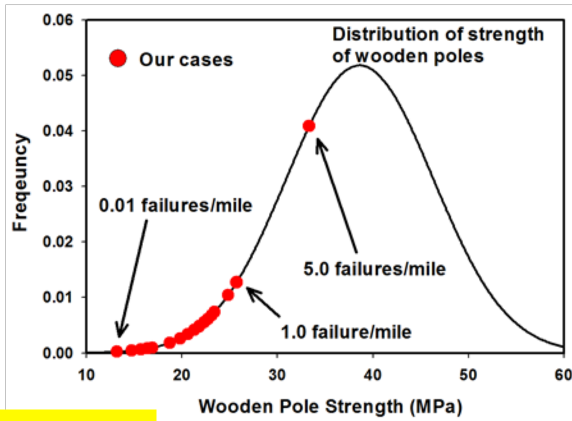
Modeling and Analysis For Extreme Event Resilience—Asset-Level Damage Modeling



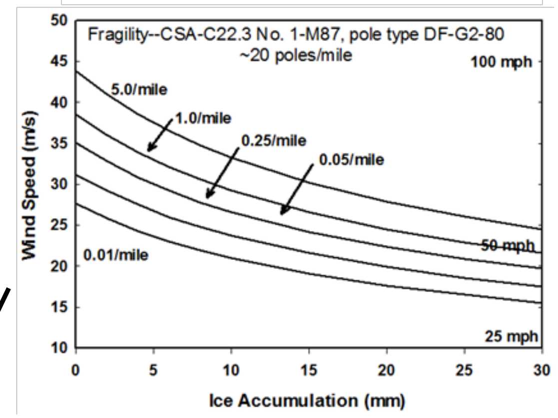
Physics/mechanical engineering model of mechanical stress on utility poles

Physics-based models of probabilistic asset failure

Test data for statistical model of utility pole ultimate strength



Failure rate of poles as function of hazard fields



Hurricane Iniki 1992 Kauai

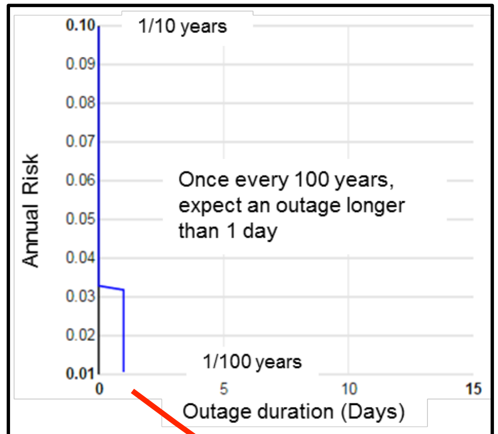
CIRCUIT	STORM 1	STORM 2	STORM 3	STORM 4	STORM 5	STORM 6	STORM 7
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0
	53	21	236	8	0	2	232
	0	1	10	0	0	0	13
	5	53	102	0	0	0	159
	0	1	4	0	0	0	4
	0	0	0	0	0	0	1
	0	4	8	0	1	0	6
	0	2	12	0	0	0	21
	0	1	5	0	0	0	5
	0	12	28	0	1	0	22
	0	0	0	0	0	0	0
	11	3	100	3	0	1	96
	0	0	4	0	0	0	5

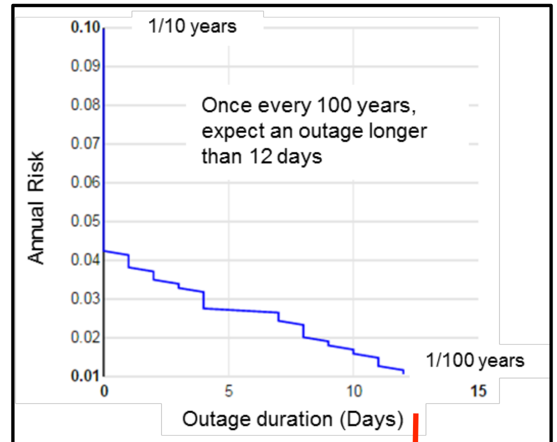
Modeling and Analysis For Extreme Event Resilience—Asset-Level/Crew-Level Restoration Modeling

Estimate the number of crews available on each day of the restoration

Limiting restoration activity

Replace poles:
2-3 poles/day/crew

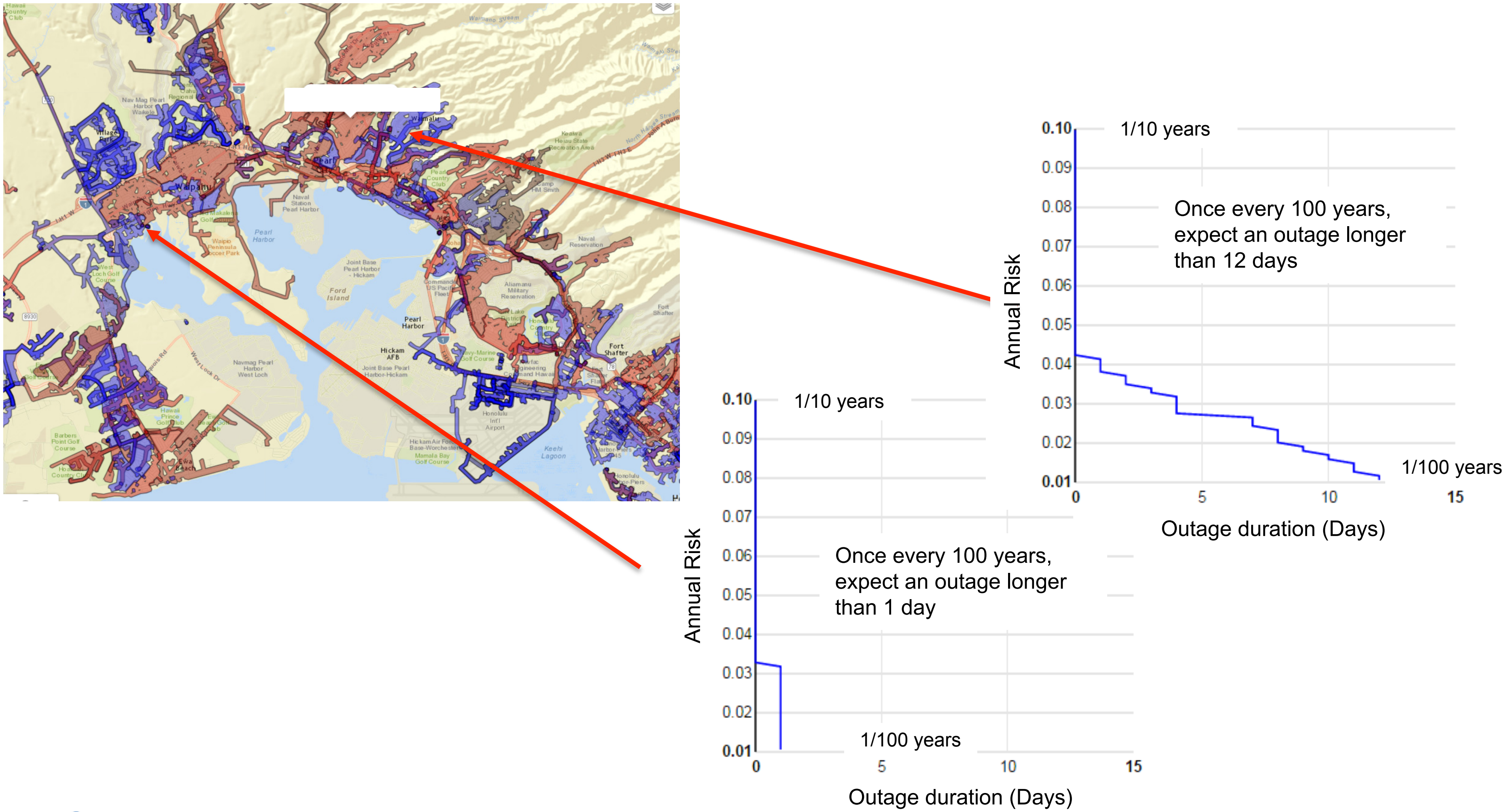




Circuit	hospitals	hospital beds	airports	potable water (wells)	waste water	military	Rank
	2-General-606 beds	606		8			1
	1-General-495 beds	495					2
	3-Gen&Rehab-400 beds	400					3
	1-General-240 beds	240					4
	1-General-235 beds	235					5
	1-Childrens-225 beds	225					6
	1-Psych-178 beds	178		2			7
	2-General&Psych-168 beds	168					8
	1-Special-164 beds	164					9
	1-General-160 beds	160					10
	1-General-126 beds	126					11
	1-General-102 beds	102		1			12
	1-General-94 beds	94					13
				2		1	14
							15
	2-General-606 beds	606					16
	1-General-495 beds	495					17
	1-General-235 beds	235					18
	1-Childrens-225 beds	225					19
	1-Special-164 beds	164					20
	1-General-160 beds	160					21
	1-General-126 beds	126					22

Circuit-level priorities

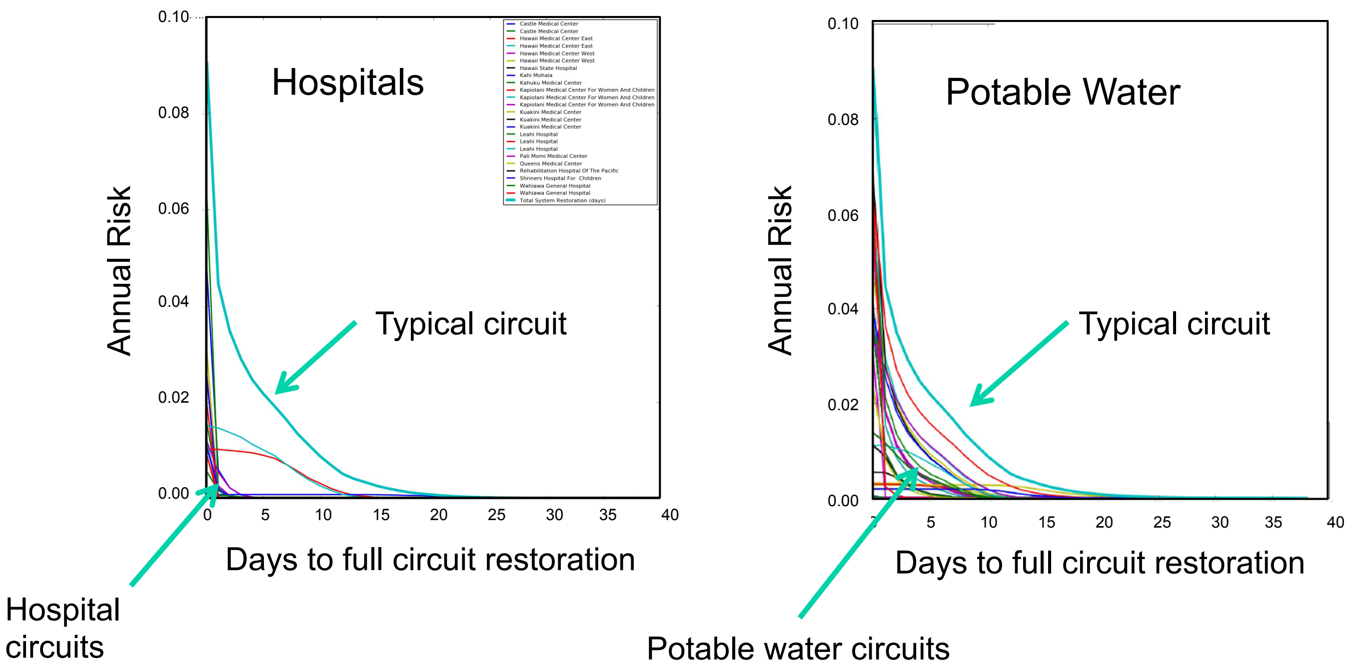
Probabilistic Risk Analysis for Each Circuit/Facility



Modeling and Analysis For Extreme Event Resilience—Systems Exhibit Naturally-Evolved Resilience

Distribution systems that have experienced extreme events have naturally evolved to protect critical loads

<u>8,000 hurricane ensemble</u>

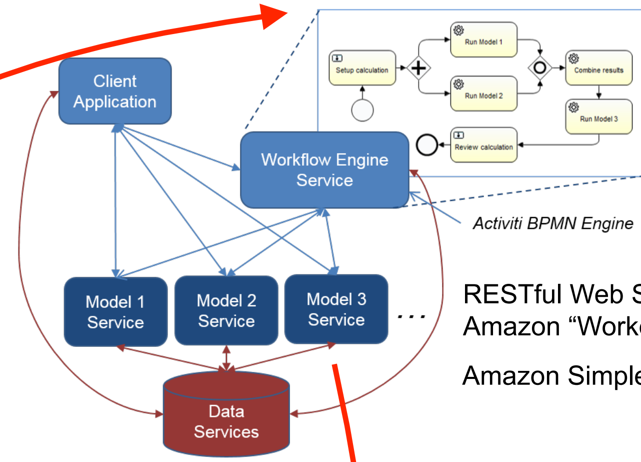


Ongoing work

- Extending to other sectors and dependent critical infrastructures
- Analyzing cost-efficient upgrade to improve resilience

Modeling and Analysis For Extreme Event Resilience—Computing Architecture and Environment

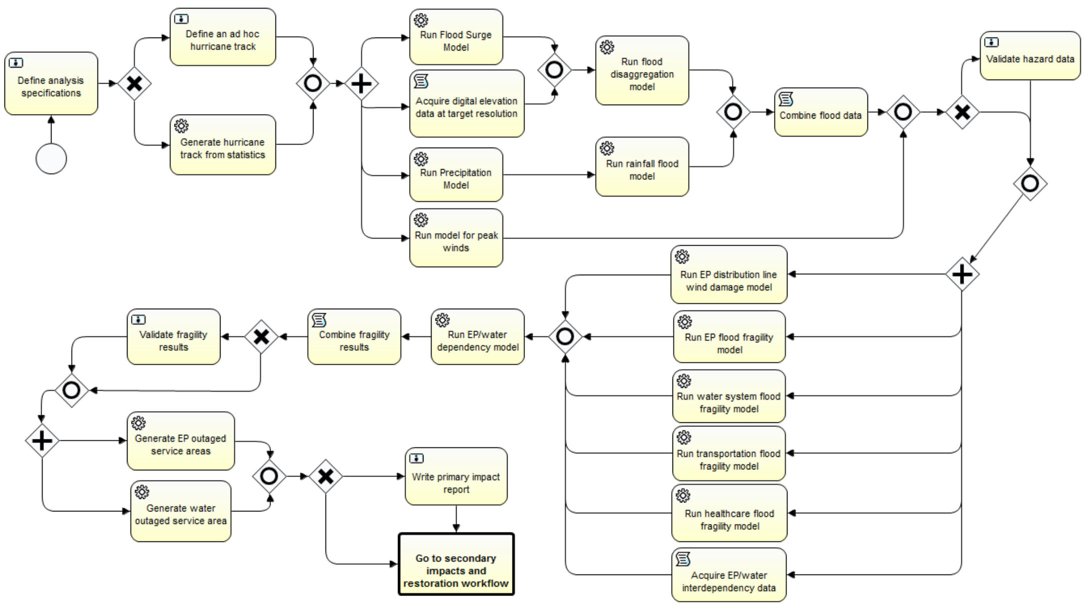
Service-Oriented Architecture



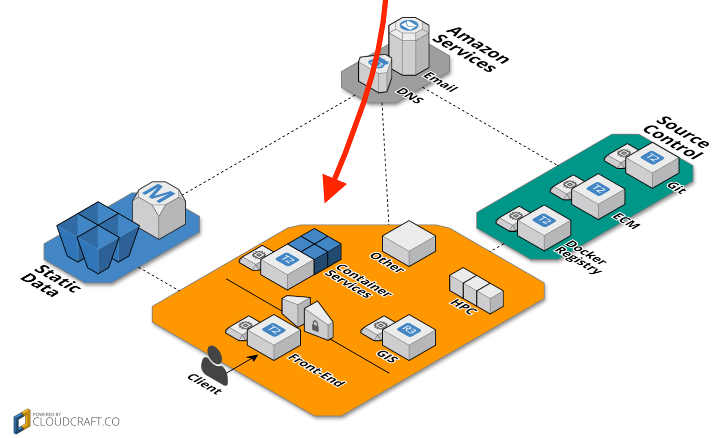
RESTful Web Services or Amazon "Workers"

Amazon Simple Work Flow

Logical Modeling Workflow



Amazon Cloud Virtual Machines



Optimal Resilient Design for Extreme Events—Basic Concepts

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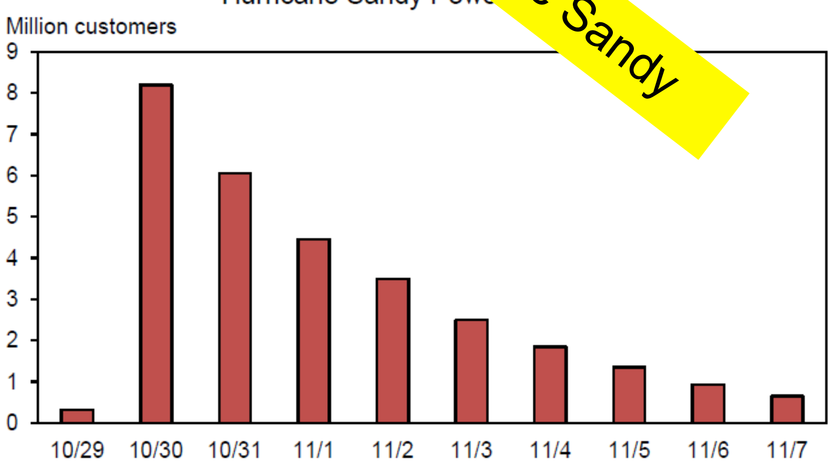
Optimal Resilient Design for Extreme Events—Basic Concepts

Hurricane Sandy Pow

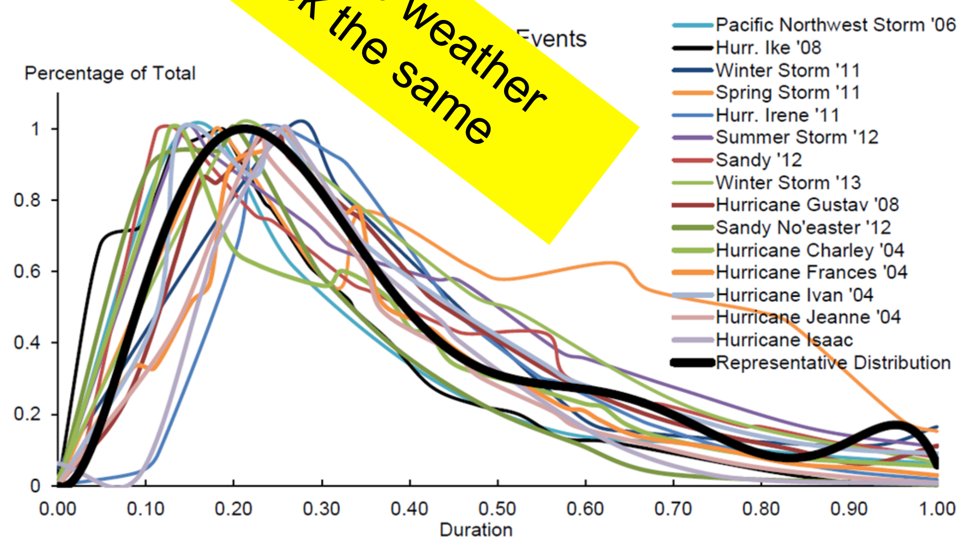


Source: Department of Energy

Hurricane Sandy

Most extreme weather events look the same

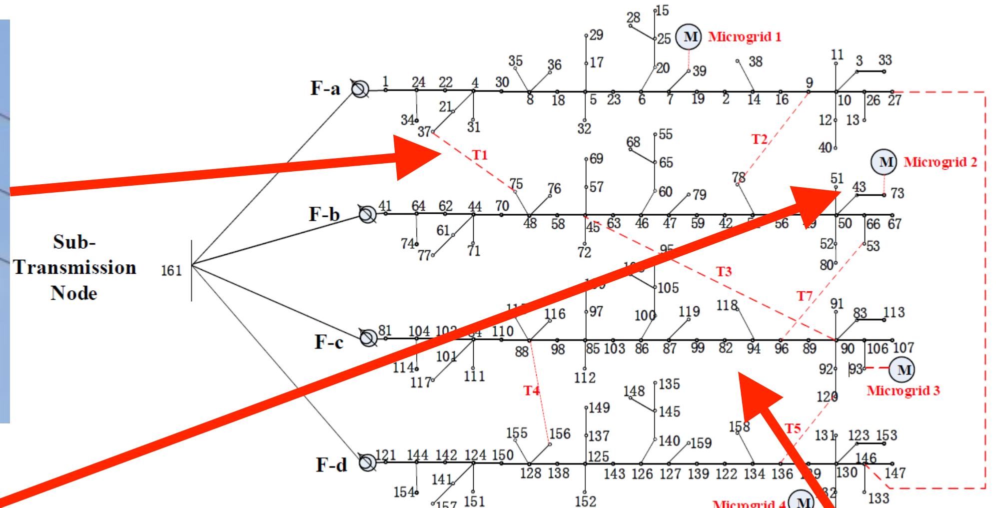
Events



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

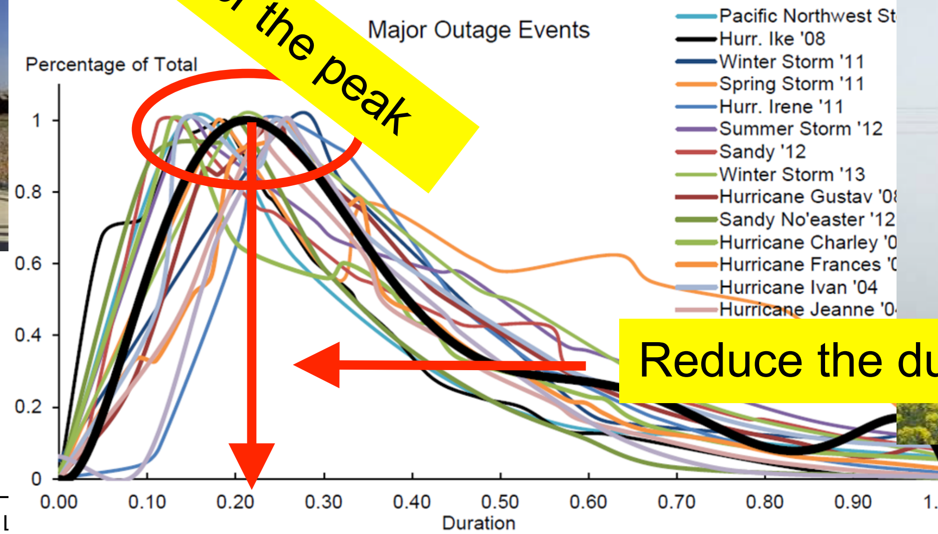
ECONOMIC BENEFITS OF INCREASING ELECTRIC GRID RESILIENCE TO WEATHER OUTAGES. Executive Office of the President , August 2013

Optimal Resilient Design for Extreme Events—Operations-Based Planning for Resilience



Kevin Schneider and Chen-Ching Liu

Lower the peak



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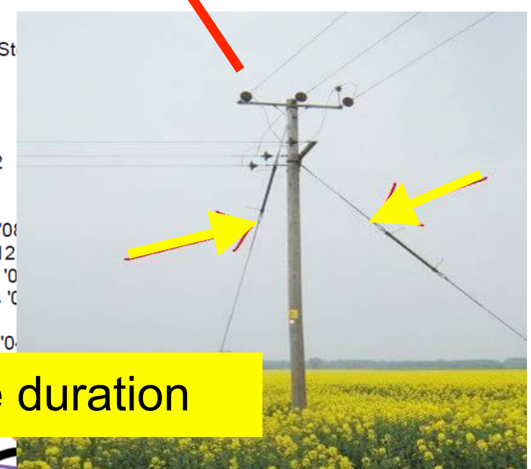


Reduce the duration

Optimal Resilient Design for Extreme Events—Formulation

minimize $\sum_{ij\in E} c_{ij}x_{ij} + \sum_{i,j\in E} \kappa_{ij}\tau_{ij} + \sum_{i\in N,k\in p_i} \zeta_i^k z_i^k + \sum_{i\in N} \mu_i u_i$ ← Min cost for upgrade

s.t.

$$-x_{ij}Q_{ij}^k|p_{ij}| \le \sum_{k\in p_{ij}} f_{ij}^k \le x_{ij}Q_{ij}^k|p_{ij}|$$

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

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

← Power flow physics and limits on switched networks

$$l_i^k = y_i d_i^k$$

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

$$g_i^k - l_i^k - \sum_{j\in N} f_{ij}^k = 0$$

← Generation and load limits

$$0 \le z_i^k \le u_i Z_i^k$$

← Generation investment size constraints

$$\sum_{ij\in s}(x_{ij} + (1-\tau_{ij})) \le |s| - 1$$

← “No Loop”/Topology switching constraints

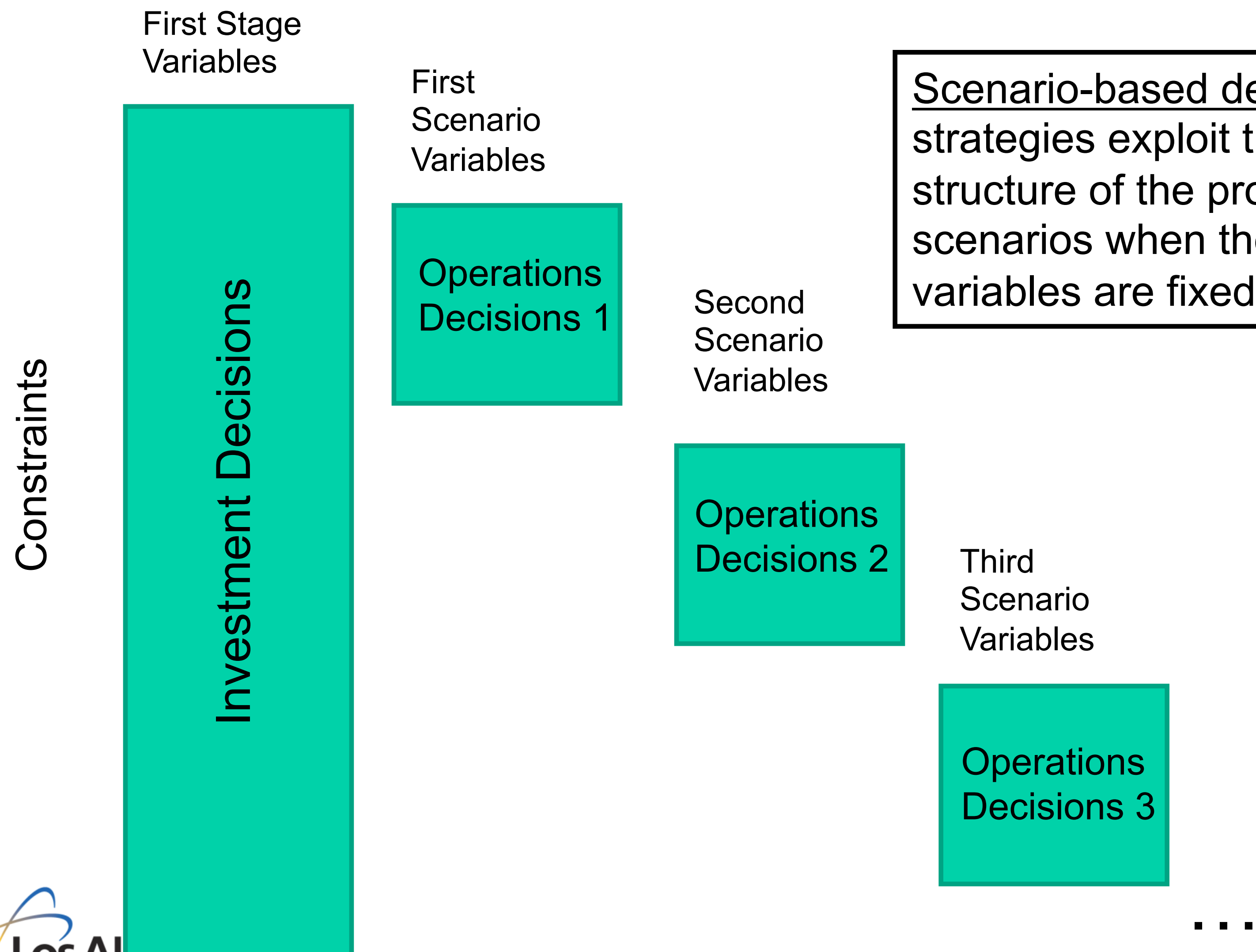
$$\sum_{i\in CL,k\in p_i} l_i^k \ge .98\sum_{i\in CL,k\in p_i} d_i^k$$

$$\sum_{i\in N\setminus L,k\in p_i} l_i^k \ge .5\sum_{i\in N\setminus L,k\in p_i} d_i^k$$

← Resilience performance

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

Optimal Resilient Design for Extreme Events—Algorithms



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

Optimal Resilient Design for Extreme Events—Algorithms

$ResilientDesign(S)$

$s \leftarrow chooseScenario(S)$

$\sigma \rightarrow solveMIP(s)$

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

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

$\sigma \rightarrow solveMIP(s)$

Solve over all damage scenarios

Select 1 scenario

Design network for damage scenario 1

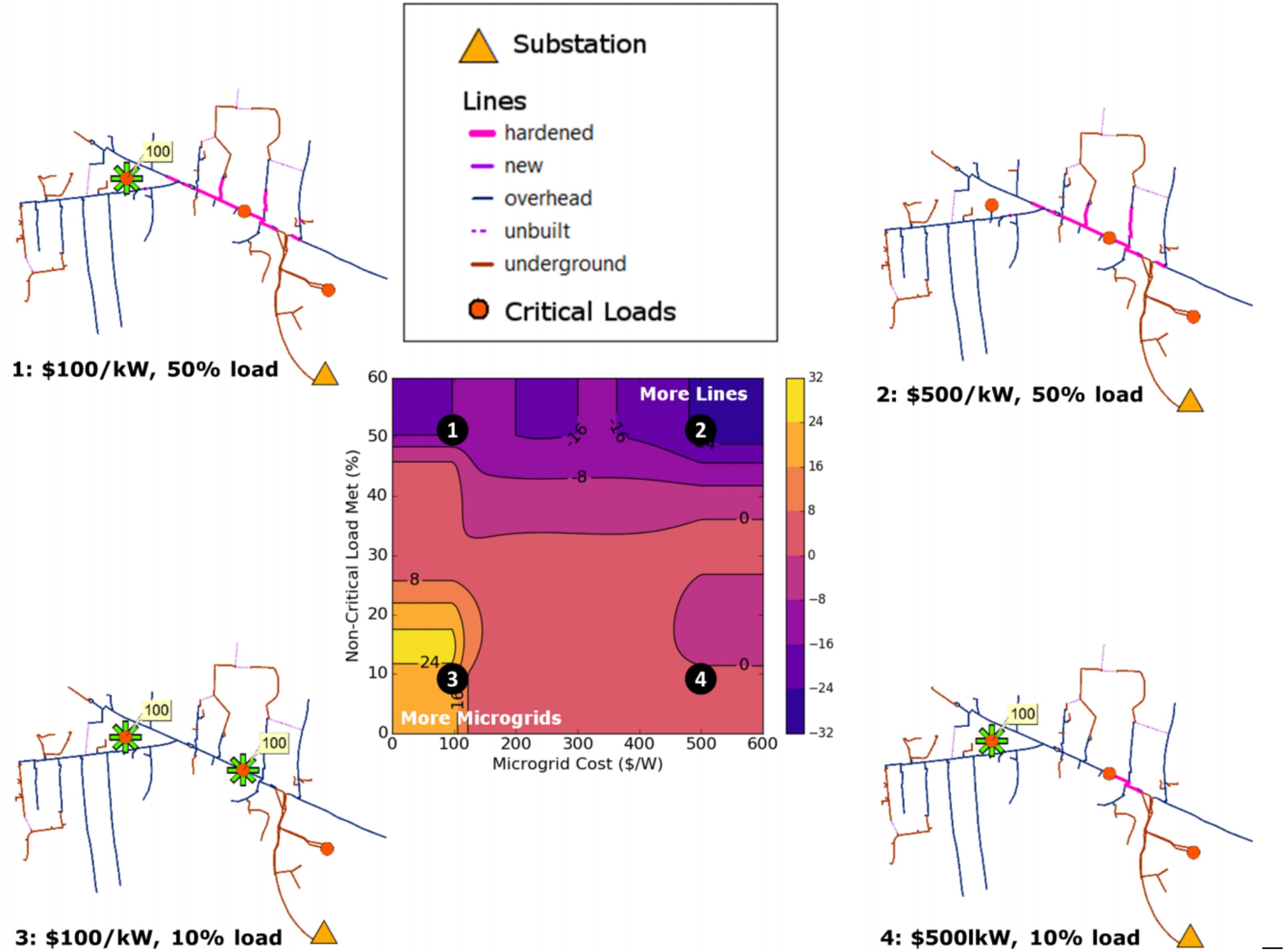
Is solution feasible for remaining scenarios

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

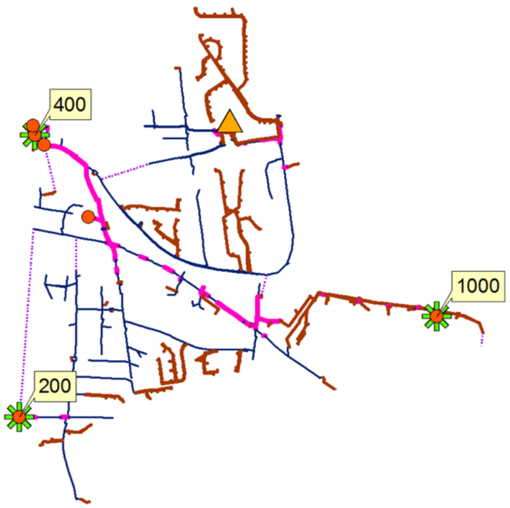
Find a new solution

Iterate until solution is feasible for all scenarios

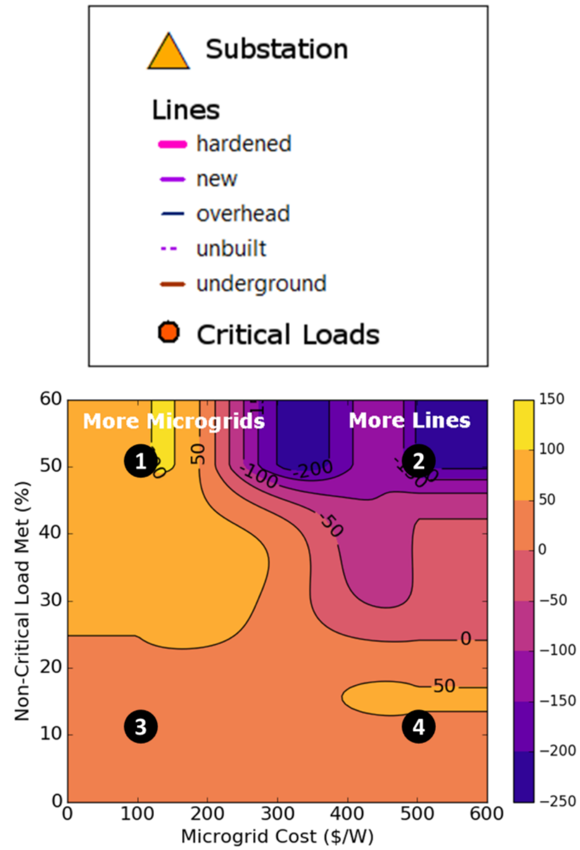
Optimal Resilient Design for Extreme Events—Results on Realistic Systems—Example #1

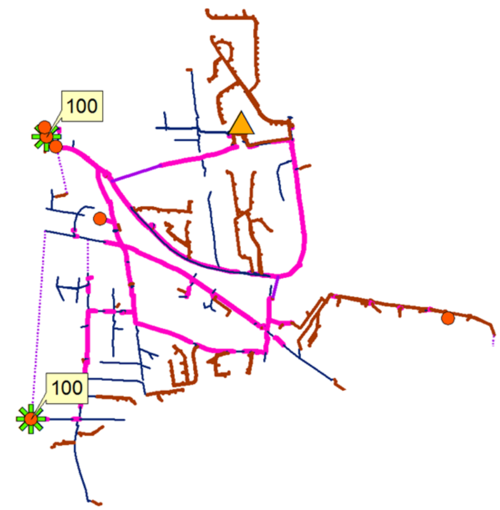


Optimal Resilient Design for Extreme Events—Results on Realistic Systems—Example #2

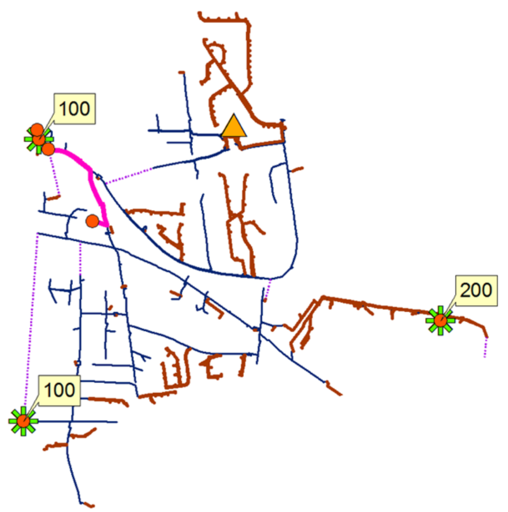


1: $100/kW, 50% load

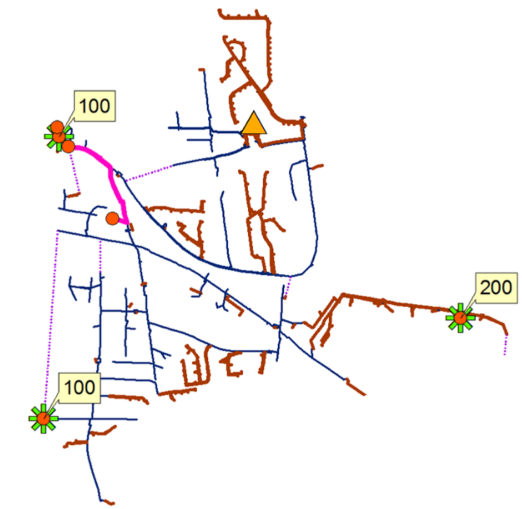




2: $500/kW, 50% load



3: $100/kW, 10% load



4: $500lkW, 10% load

Electric Power Hardening and Resilience Models—Coarse-Grained Representation of Adpatation

Damage model is a statistical correlation between the maximum sustained wind speed and the number of customer accounts without power

Source data does not differentiate between

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- Inundation damage to transformers/substations

Not extensible to other hazard fields, e.g. peak ground acceleration

Applied at the substation service area resolution

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Cannot resolve:

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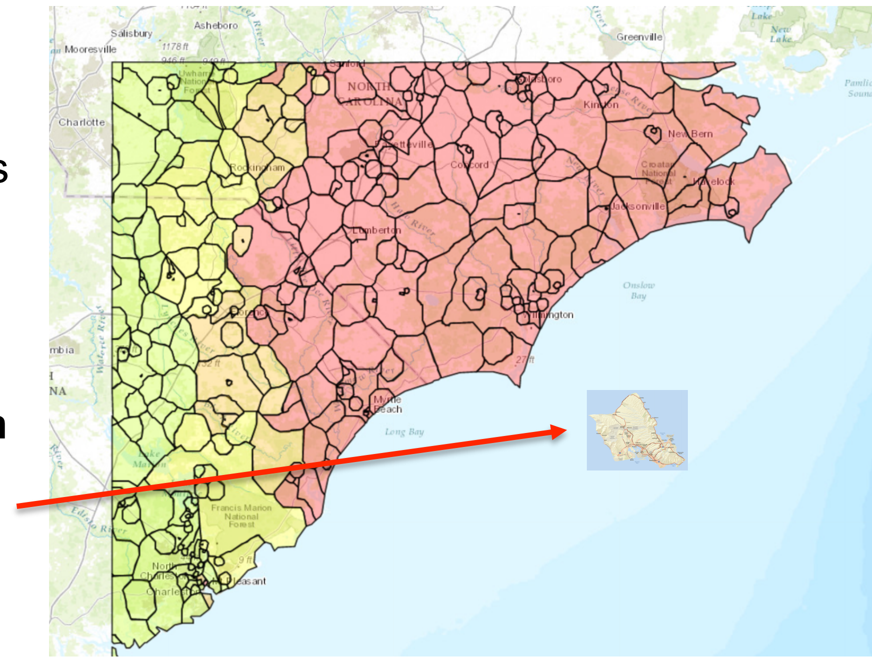

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Physics, Control, Optimization, Computer Science, Statist… …rations Research, Power Engineering

Next Event January 2019

Students From: Columbia, Rutgers, MIT, CalTech, … …ch, UC Berkeley, UCSD, UCSB, UTexas, UVermont, UMinnesota, UMichigan, UWashi… …Conn, NICTA Australia, Skolkovo Tech, LANL

Lecturers: I. Hiskens, UMi…

A. Conejo, OSU; **F. Dorfler**, … …h

M. Chertkov, LANL; D. Bienstock, … …bia

S. Low, Cal Tech; P. van Hen… …ICTA Australia

K. Turitsyn, MIT; D. Callaw… UC Berkeley

“The uniqueness of this workshop is inarguable”

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