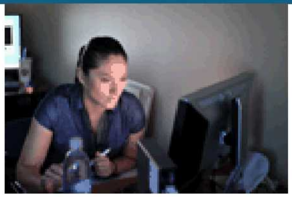
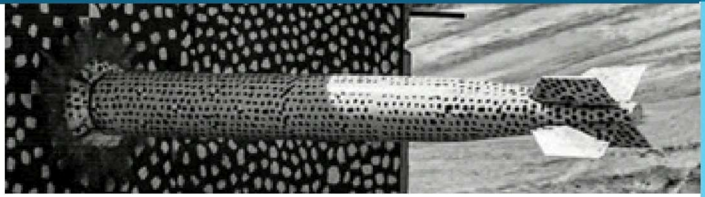
SAND2018-12589C

Co-optimization to Integrate Power System Reliability Decisions with Resiliency Decisions





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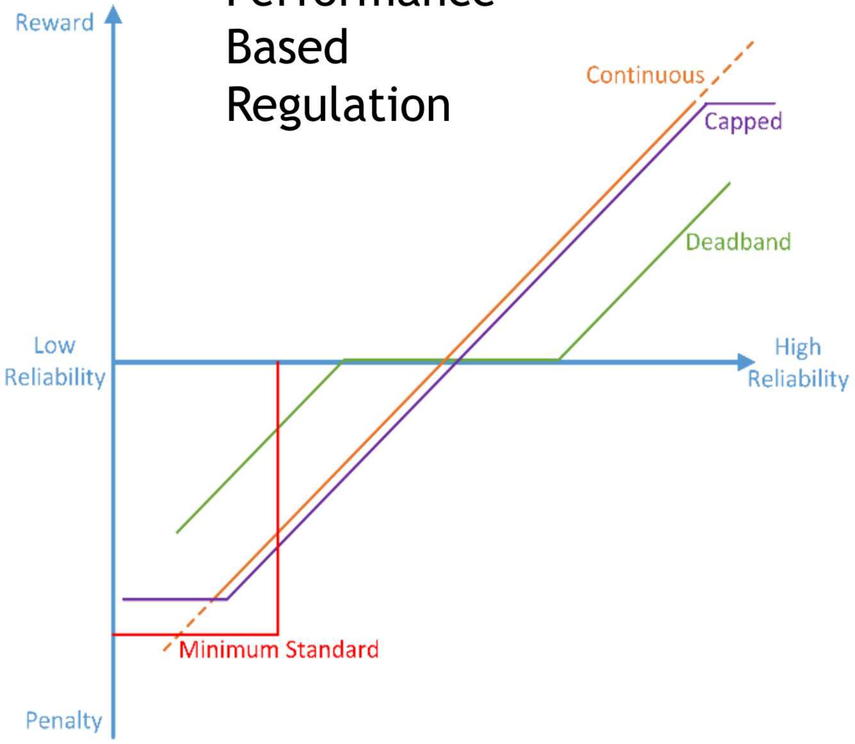
Problem Statement

- **National security problem being addressed:**
  - Help electric utilities prepare and plan for catastrophic events through optimal investments
  - Power system utilities often have incentives to become more reliable, however there are not similar incentives to promote investments in resilience.
  - Reliability metrics such as SAIDI and SAIFI, remove resilience events (low probability-high consequence events), reducing utilities incentives to improve resilience even further

Performance Based Regulation



Solution Approaches

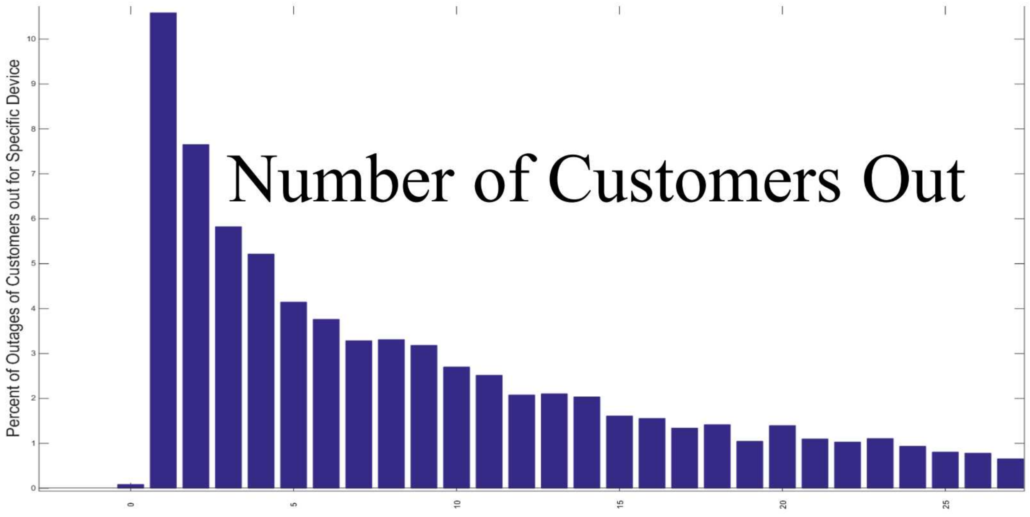
- The goal is to come up with optimization models to determine the optimal investments to improve both resiliency and reliability.

- Help utilities be more proactive rather than reactive.

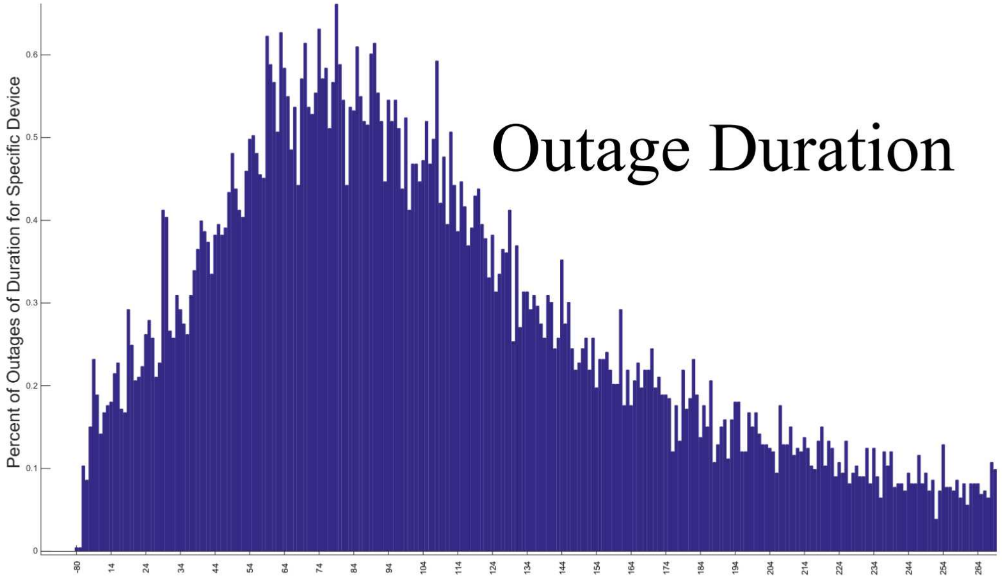
- Models/algorithms developed:
  1. Stochastic mixed integer program for optimal reliability investments
  2. Generalized dynamic programming algorithm for optimal reliability investments
  3. A stochastic mixed integer program for optimal resilience investments
  4. A two-stage stochastic generalized disjunctive programming formulation for optimal resilience investments
  5. A co-optimization technique for creating a pareto frontier of reliability vs resiliency.

Data Considerations as Inputs to Optimization Models

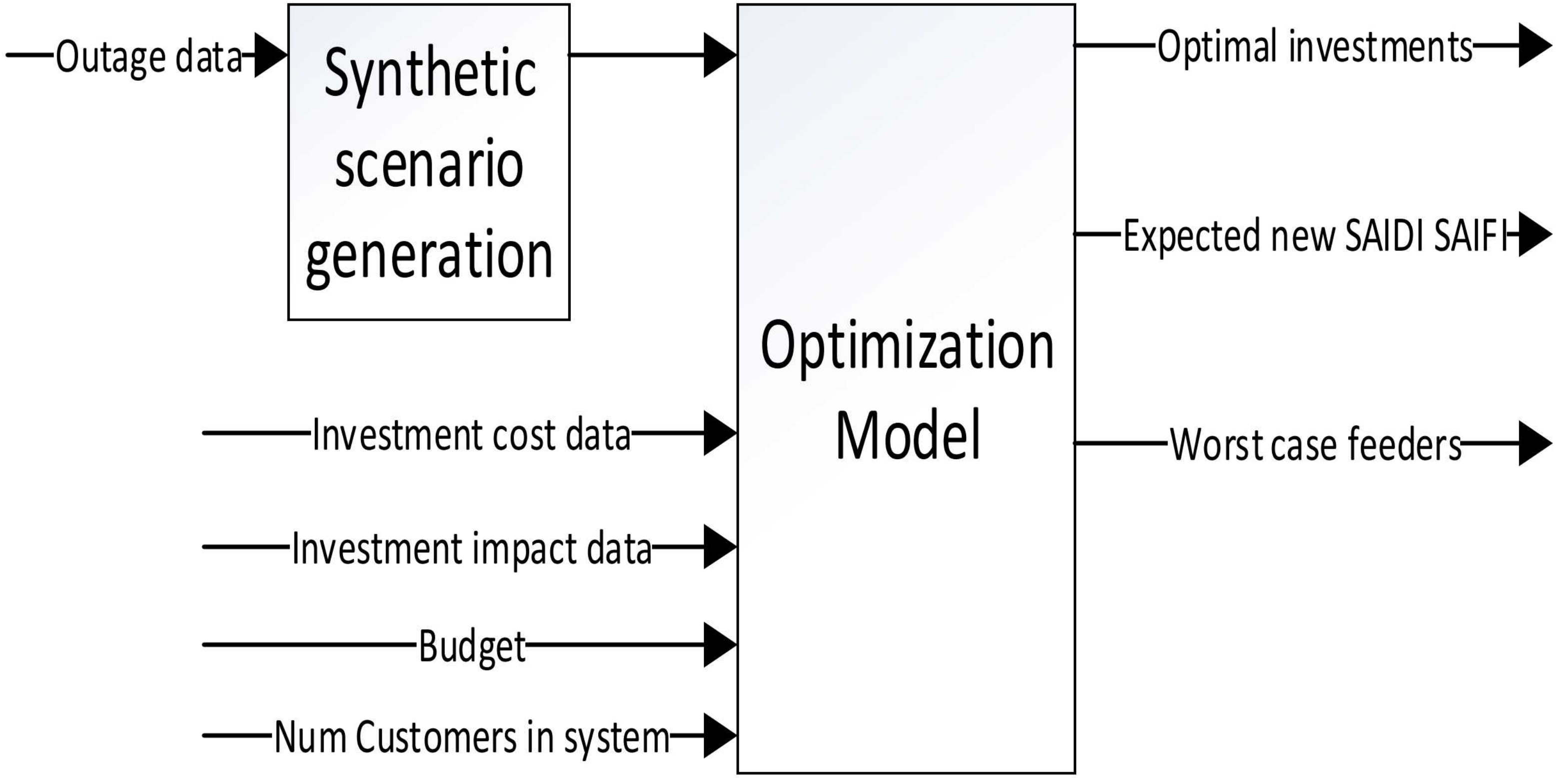
- **Reliability models**
  - The reliability models takes historical outage data.
  - This is typically high quality data, high quantity data.
  - Utilities record every outage on there systems for years.
  - We leverage the quality data in the model and synthesize more data for scaling experimentation.



- **Resilience models**
  - The models utilizes scenarios of certain threats as its primary input.
  - Each scenario includes outaged components and time.
  - Creating scenarios of hurricanes, earthquakes, etc. is a whole research topic on its own.
  - Historical data of these large scale events and how they impact a power system is limited.



Reliability Investment Modeling



Stochastic nonlinear MIP for optimal reliability investments

$$min \sum_{\omega \in \Omega} \frac{SAIDI_{up}^{\omega}}{SAIDI_{syn}} + \frac{SAIFI_{up}^{\omega}}{SAIFI_{syn}}$$

subject to

$$\sum_{i,d,u \in U_{i,d}} c_u y_{i,d,u} \leq B$$

Budget constraint

$$SAIFI_{up}^{\omega} = \frac{1}{N} \sum_{o \in O_{\omega}} CO_o TO_o \qquad \forall \omega \in \Omega$$

SAIFI definition

$$SAIFI_{up}^{\omega} = \frac{1}{N} \sum_{o \in O_{\omega}} CO_o \qquad \forall \omega \in \Omega$$

SAIDI definition

$$CO_o = \min_{u \in U_o} \{C_{o,u} y_{i_o,d_o,u} + C_o(1 - y_{i_o,d_o,u})\} \quad \forall \omega \in \Omega, o \in O_{\omega}$$

$$TO_o = \min_{u \in V_o} \{T_{o,u} y_{i_o,d_o,u} + T_o(1 - y_{i_o,d_o,u})\} \quad \forall \omega \in \Omega, o \in O_{\omega}$$

Fundamental Assumption: duration and number of customers affected post-upgrades is determined entirely by most effective upgrades.

Number of customers affected and duration as a result of upgrade u only

Linearization Technique

$$CO_o \le C_{o,u} y_{i_o,d_o,u} + C_o(1 - y_{i_o,d_o,u}) \quad \forall o \in O, u \in U_o$$
$$CO_o \ge C_{o,u}[y_{i_o,d_o,u} + C_o(1 - y_{i_o,d_o,u})] m_{o,u} \; \forall o \in O, u \in U_o$$
$$\sum_{u \in U_o} m_{o,u} = 1 \quad \forall o \in O$$

Replace calculation of number of customers affected with these three constraints

$$TO_o \le T_{o,u} y_{i_o,d_o,u} + T_o(1 - y_{i_o,d_o,u}) \quad \forall o \in O, u \in V_o$$
$$TO_o \ge T_{o,u}[y_{i_o,d_o,u} + T_o(1 - y_{i_o,d_o,u})] n_{o,u}$$
$$\sum_{u \in V_o} n_{o,u} = 1 \quad \forall o \in O$$

Replace calculation of duration with these three constraints

$$my_{o,u} \le m_{o,u} \quad \forall o \in O, u \in U_o$$
$$my_{o,u} \le y_{i_o,d_o,u} \quad \forall o \in O, u \in U_o$$
$$my_{o,u} \ge m_{o,u} + y_{i_o,d_o,u} + 1 \quad \forall o \in O, u \in U_o$$
$$ny_{o,u} \le n_{o,u} \quad \forall o \in O, u \in V_o$$
$$ny_{o,u} \le y_{i_o,d_o,u} \quad \forall o \in O, u \in V_o$$
$$ny_{o,u} \ge n_{o,u} + y_{i_o,d_o,u} + 1 \quad \forall o \in O, u \in V_o$$

Deal with resulting product of binary variables with these six constraints.

$$COTO_o = \sum_{u \in U_o} \sum_{u' \in V_o} C_{o,u} T_{o,u'} m_{o,u} n_{o,u'} \quad \forall o \in O$$

Product of customers affected and duration takes a finite number of values and can be calculated through binaries.

$$mn_{o,u,u'} \le m_{o,u} \quad \forall o \in O, u \in U_o, u' \in V_o$$
$$mn_{o,u,u'} \le n_{o,u'} \quad \forall o \in O, u \in U_o, u' \in V_o$$
$$mn_{o,u,u'} \ge m_{o,u} + n_{o,u'} + 1 \quad \forall o \in O, u \in U_o, u' \in V_o$$

Deal with resulting product of binary variables.

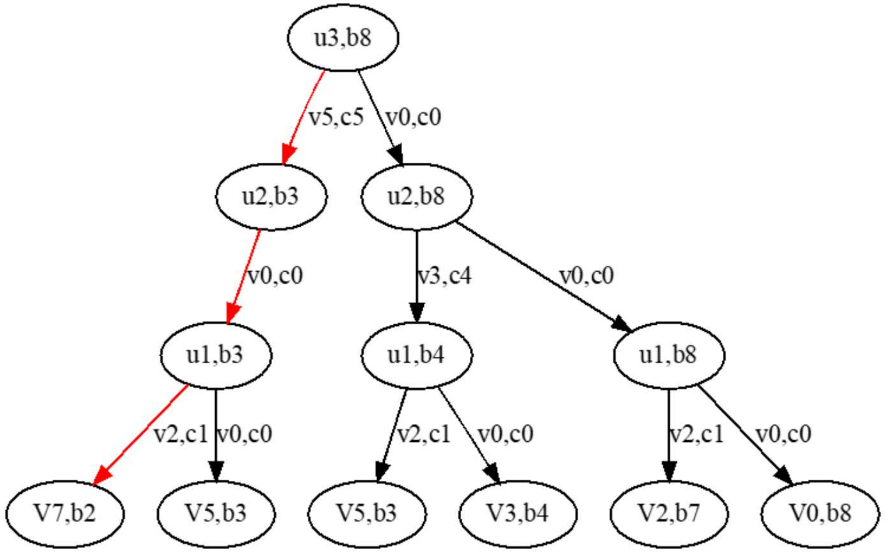
Generalized dynamic programming algorithm

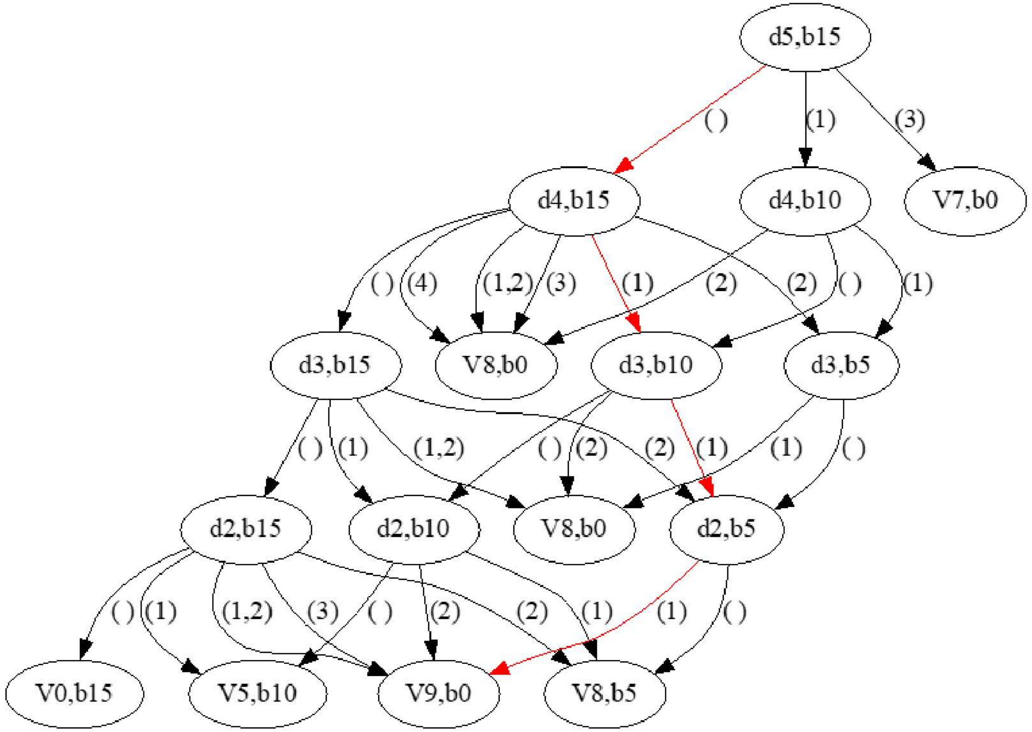
Classic Dynamic Programming Algorithm for 0-1 Knapsack Problem

- Effectively search binary tree where each node decides whether or not to make purchase
- Efficiency stems from use of cache which eliminates redundant calculations.

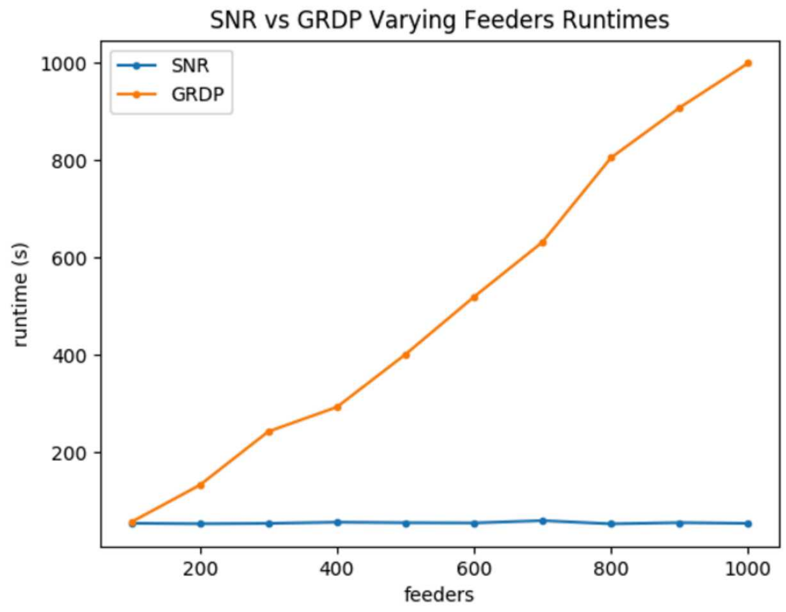
Generalized Dynamic Programming Algorithm

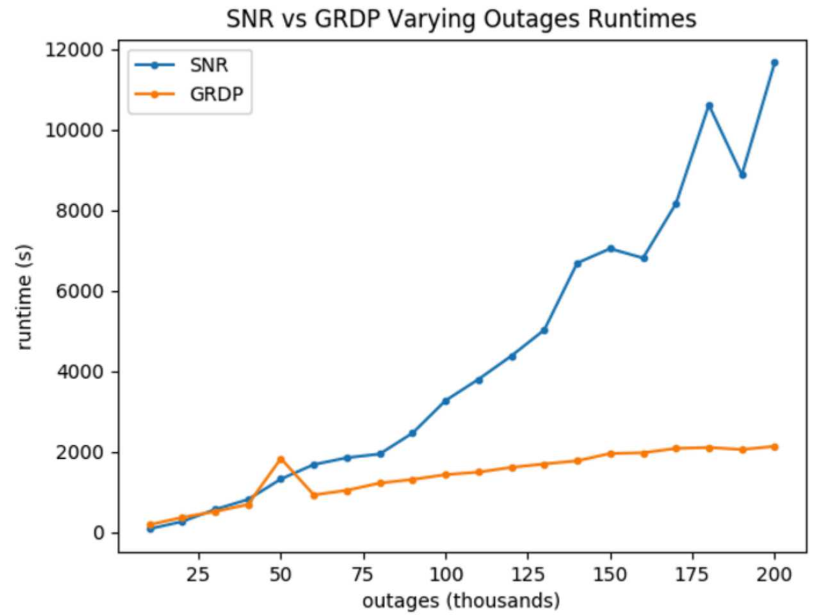
- Effectively searches a tree where each node represents a feeder, device pair. Emanating edges represent packages of upgrades that can be purchased to improve resiliency for that feeder, device pair.
- Efficiency here also stems from use of a cache.

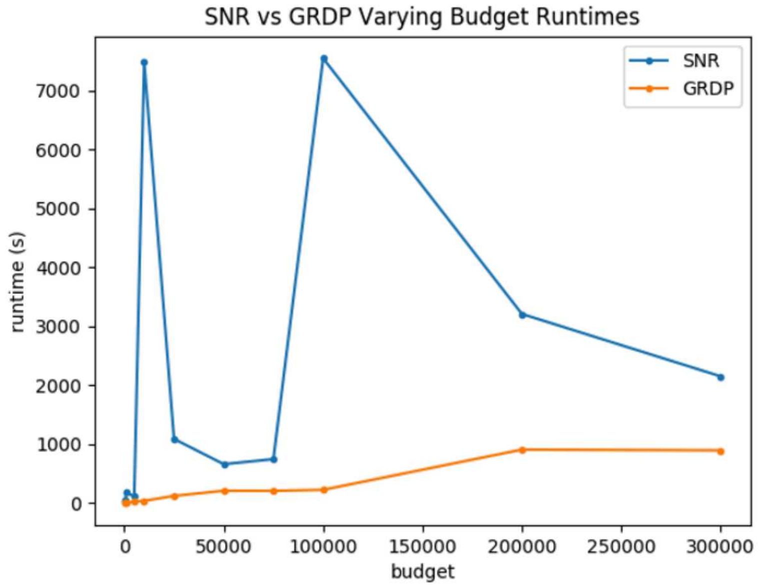


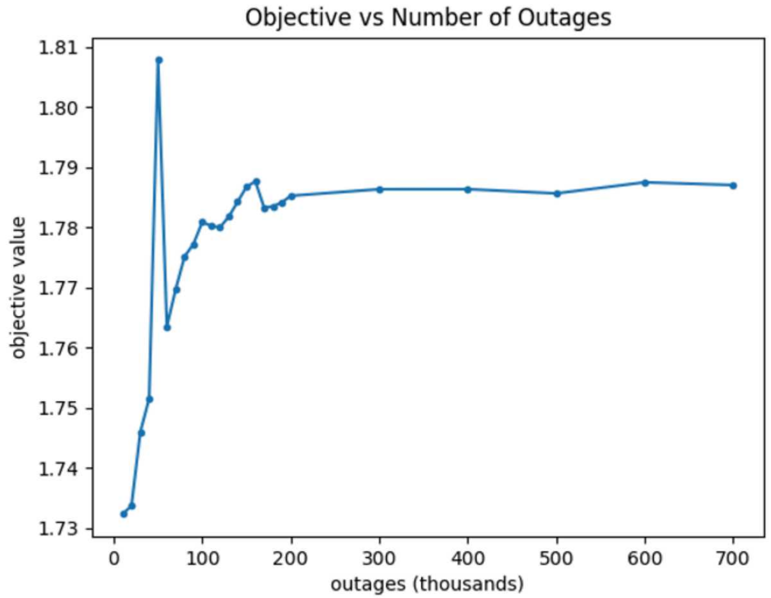


Results


SNR vs GRDP Varying Feeders Runtimes
SNR
GRDP
runtime (s)
feeders
200
400
600
800
1000


SNR vs GRDP Varying Outages Runtimes
SNR
GRDP
runtime (s)
outages (thousands)
0
2000
4000
6000
8000
10000
12000
25
50
75
100
125
150
175
200


SNR vs GRDP Varying Budget Runtimes
SNR
GRDP
runtime (s)
budget
0
1000
2000
3000
4000
5000
6000
7000
50000
100000
150000
200000
250000
300000


Objective vs Number of Outages
objective value
outages (thousands)
1.73
1.74
1.75
1.76
1.77
1.78
1.79
1.80
1.81
0
100
200
300
400
500
600
700

Stochastic mixed integer program for optimal resilience investments

$$\min \sum_{\omega\in\Omega} q_\omega \left(\frac{1}{B_1} \sum_{t\in\mathcal{T}} t \sum_{b\in\mathcal{B}} A_b p^{\omega}_{b,t} + \frac{1}{B_2} \sum_{b\in\mathcal{B}} A_b p^{\omega}_{b,1} \right)$$

s.t.

Budget

$$\sum_{b\in\mathcal{B}} C_b z_b + \sum_{l\in\mathcal{L}} C_l z_l + \sum_{g\in\mathcal{G}} C_g z_g \leq K$$

Unit Commitment

$$\sum_{g\in\mathcal{G}_b} p^{\omega}_{g,t} + \sum_{l\in\mathcal{L}^{\text{to}}_b} p^{\omega}_{l,t} - \sum_{l\in\mathcal{L}^{\text{from}}_b} p^{\omega}_{l,t} = D_b - p^{\omega}_{b,t} \qquad \forall b\in\mathcal{B}, \forall t\in T, \forall\omega\in\Omega$$

$$p^{\omega}_{g,t} - p^{\omega}_{g,t-1} \leq (SU_g - \underline{P}_g - RU_g)v^{\omega}_{g,t} + (\underline{P}_g + RU_g)u^{\omega}_{g,t} - \underline{P}_g u^{\omega}_{g,t-1} \qquad \forall g\in\mathcal{G}, \forall t\in T, \forall\omega\in\Omega$$

$$p^{\omega}_{g,t-1} - p^{\omega}_{g,t} \leq (SD_g - \underline{P}_g - RD_g)w^{\omega}_{g,t} + (\underline{P}_g + RD_g)u^{\omega}_{g,t-1} - \underline{P}_g u^{\omega}_{g,t} \qquad \forall g\in\mathcal{G}, \forall t\in T, \forall\omega\in\Omega$$

$$u^{\omega}_{g,t} - u^{\omega}_{g,t-1} = v^{\omega}_{g,t} - w^{\omega}_{g,t} \qquad \forall g\in\mathcal{G}, \forall t\in T, \forall\omega\in\Omega$$

$$v^{\omega}_{g,t} \leq u^{\omega}_{g,t} \qquad \forall g\in\mathcal{G}, \forall t\in T, \forall\omega\in\Omega$$

$$u^{\omega}_{g,t} \leq 1 - w^{\omega}_{g,t} \qquad \forall g\in\mathcal{G}, \forall t\in T, \forall\omega\in\Omega$$

$$\underline{P}_g u^{\omega}_{g,t} \leq p^{\omega}_{g,t} \leq \overline{P}_g u^{\omega}_{g,t} \qquad \forall g\in\mathcal{G}, \forall t\in T, \forall\omega\in\Omega$$

$$0 \leq p^{\omega}_{b,t} \leq D_b \qquad \forall b\in\mathcal{B}, \forall t\in T, \forall\omega\in\Omega$$

Transmission Switching

$$p^{\omega}_{l,t} = y^{\omega}_{l,t} S_l(\theta^{\omega}_{B^{\text{to}}_l,t} - \theta^{\omega}_{B^{\text{from}}_l,t}) \qquad \forall l\in\mathcal{L}, \forall t\in T, \forall\omega\in\Omega$$

$$-\frac{\pi}{3} \leq \theta^{\omega}_{B^{\text{to}}_l,t} - \theta^{\omega}_{B^{\text{from}}_l,t} \leq \frac{\pi}{3} \qquad \forall l\in\mathcal{L}, \forall t\in T, \forall\omega\in\Omega$$

$$-\overline{P}_l y^{\omega}_{l,t} \leq p^{\omega}_{l,t} \leq \overline{P}_l y^{\omega}_{l,t} \qquad \forall l\in\mathcal{L}, \forall t\in T, \forall\omega\in\Omega$$

Effects of Investment Decisions

$$y^{\omega}_{l,t} \leq z_l \qquad \forall l\in\mathcal{L}, \forall t\leq X_l$$

$$u^{\omega}_{g,t} \leq z_g \qquad \forall g\in\mathcal{G}, \forall t\leq X_g$$

$$u^{\omega}_{g,t} \leq z_b \qquad \forall b\in B, \forall g\in\mathcal{G}_b, \forall t\leq X_b$$

$$y^{\omega}_{l,t} \leq z_b \qquad \forall b\in\mathcal{B}, \forall l\in\mathcal{L}^{\text{to}}_b \cup L^{\text{from}}_b, \forall t\leq X_b$$

A two-stage stochastic generalized disjunctive programming formulation for optimal resilience investments

$$\min \quad \sum_{\omega\in\Omega} q_\omega \left(\frac{1}{B_1} \sum_{t\in T} t \sum_{b\in\mathcal{B}} A_b p^{\omega}_{b,t} + \frac{1}{B_2} \sum_{b\in\mathcal{B}} A_b p^{\omega}_{b,1} \right)$$

$$\text{s.t.} \quad \sum_{b\in\mathcal{B}} k_b + \sum_{l\in\mathcal{L}} k_l + \sum_{g\in\mathcal{G}} k_g \le K$$

$$\sum_{g\in\mathcal{G}_b} p^{\omega}_{g,t} + \sum_{l\in\mathcal{L}^{\text{to}}_b} p^{\omega}_{l,t} - \sum_{l\in\mathcal{L}^{\text{from}}_b} p^{\omega}_{l,t} = D_b - p^{\omega}_{b,t} \quad \forall b\in\mathcal{B}, \forall t\in T, \forall\omega\in\Omega$$

$$\begin{bmatrix} y^{\text{on}}_{g,t,\omega} \\ \underline{P}_g \le p^{\omega}_{g,t} \\ \underline{P}_g \le p^{\omega}_{g,t-1} \\ -RD_g \le p^{\omega}_{g,t} - p^{\omega}_{g,t-1} \\ p^{\omega}_{g,t} - p^{\omega}_{g,t-1} \le RU_g \end{bmatrix} \vee \begin{bmatrix} y^{\text{off}}_{g,t,\omega} \\ p^{\omega}_{g,t} = 0 \\ p^{\omega}_{g,t-1} \le SD_g \end{bmatrix} \vee \begin{bmatrix} y^{\text{startup}}_{g,t,\omega} \\ \underline{P}_g \le p^{\omega}_{g,t} \le SU_g \\ p^{\omega}_{g,t-1} = 0 \end{bmatrix} \quad \forall g\in\mathcal{G}, \forall t\in T, \forall\omega\in\Omega$$

Generator constraints given status of unit (on, off, or in startup mode

$$y^{\text{on}}_{g,t,\omega} \veebar y^{\text{off}}_{g,t,\omega} \veebar y^{\text{startup}}_{g,t,\omega} = True \quad \forall g\in\mathcal{G}, \forall t\in T, \forall\omega\in\Omega$$

Unit can only be in one mode

$$\begin{bmatrix} y^{\omega}_{l,t} \\ p^{\omega}_{l,t} = S_l(\theta^{\omega}_{B^{\text{to}}_l,t} - \theta^{\omega}_{B^{\text{from}}_l,t}) \end{bmatrix} \vee \begin{bmatrix} \neg y^{\omega}_{l,t} \\ p^{\omega}_{l,t} = 0 \end{bmatrix} \quad \forall l\in\mathcal{L}, \forall t\in T, \forall\omega\in\Omega$$

A transmission line either satisfies B-theta constraint or there is no power flowing on it.

$$\begin{bmatrix} z_l \\ k_l = C_l \end{bmatrix} \vee \begin{bmatrix} \neg z_l \\ k_l = 0 \\ p^{\omega}_{l,t} = 0 \ \forall t \le X_l \end{bmatrix} \quad \forall l\in\mathcal{L}$$

$$\begin{bmatrix} z_g \\ k_g = C_g \end{bmatrix} \vee \begin{bmatrix} \neg z_g \\ k_g = 0 \\ p^{\omega}_{g,t} = 0 \ \forall t \le X_g \end{bmatrix} \quad \forall g\in\mathcal{G}$$

$$\begin{bmatrix} z_b \\ k_b = C_b \end{bmatrix} \vee \begin{bmatrix} \neg z_b \\ k_b = 0 \\ p^{\omega}_{l,t} = 0 \quad \forall t \le X_b, \forall l\in\mathcal{L}_b \\ p^{\omega}_{g,t} = 0 \quad \forall t \le X_b, \forall g\in G_b \end{bmatrix} \quad \forall b\in\mathcal{B}$$

Invest in a component and pay the price or experience outage in connected components.

$$0 \le p^{\omega}_{b,t} \le D_b \quad \forall b\in\mathcal{B}, \forall t\in T, \forall\omega\in\Omega$$

$$0 \le p^{\omega}_{g,t} \le \overline{P}_g \quad \forall g\in\mathcal{G}, \forall t\in T, \forall\omega\in\Omega$$

$$-\overline{P}_l \le p^{\omega}_{l,t} \le \overline{P}_l \quad \forall l\in\mathcal{L}, \forall t\in T, \forall\omega\in\Omega$$

$$-\frac{\pi}{3} \le \theta^{\omega}_{B^{\text{to}}_l,t} - \theta^{\omega}_{B^{\text{from}}_l,t} \le \frac{\pi}{3} \quad \forall l\in\mathcal{L}, \forall t\in T, \forall\omega\in\Omega$$

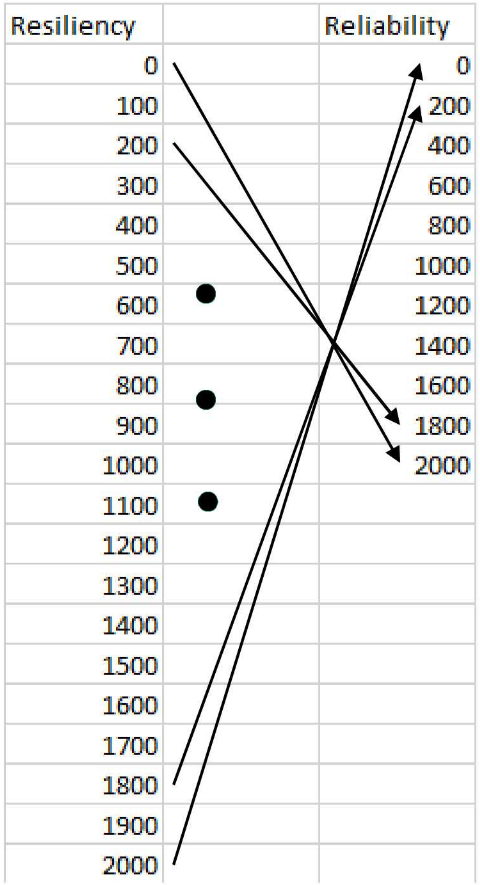
Cooptimization

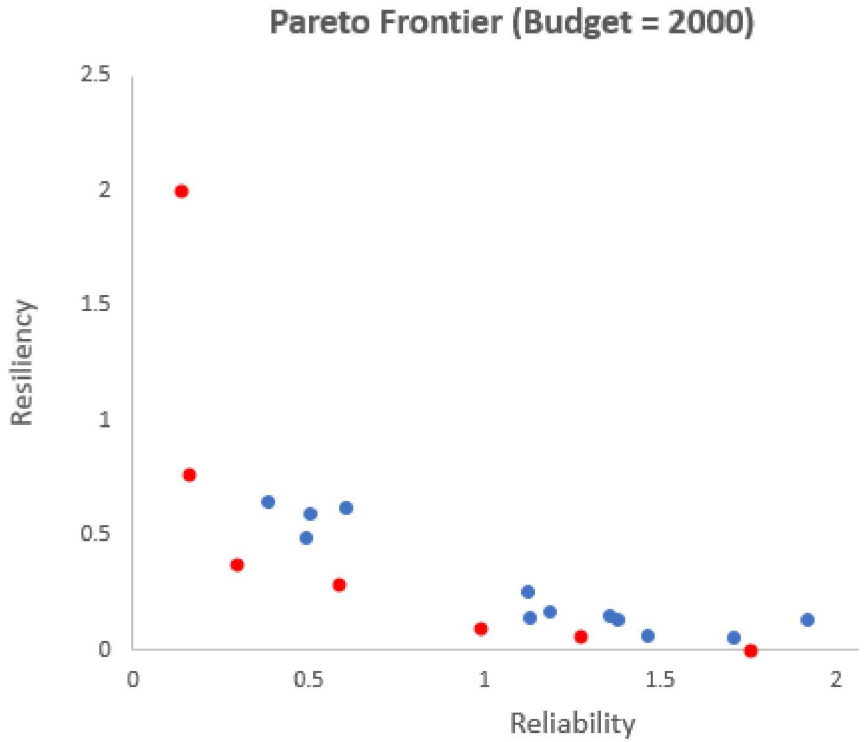
- Solve both models for a range of budgets. For each model, use the great common divisor of all investment costs to determine appropriate increment for range of budgets.

- For a fixed budget, pair resiliency and reliability results for respective budgets that add up to the fixed budget.

- Remove any Pareto-dominated points to obtain pareto frontier.

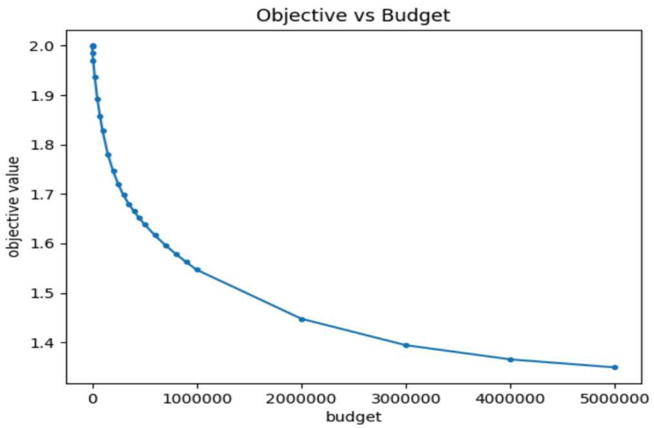
Model Budget Ranges



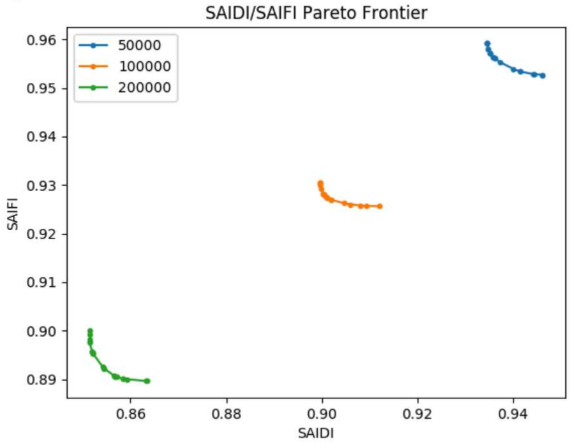


Some Results

Basic Reliability results on Full utility data

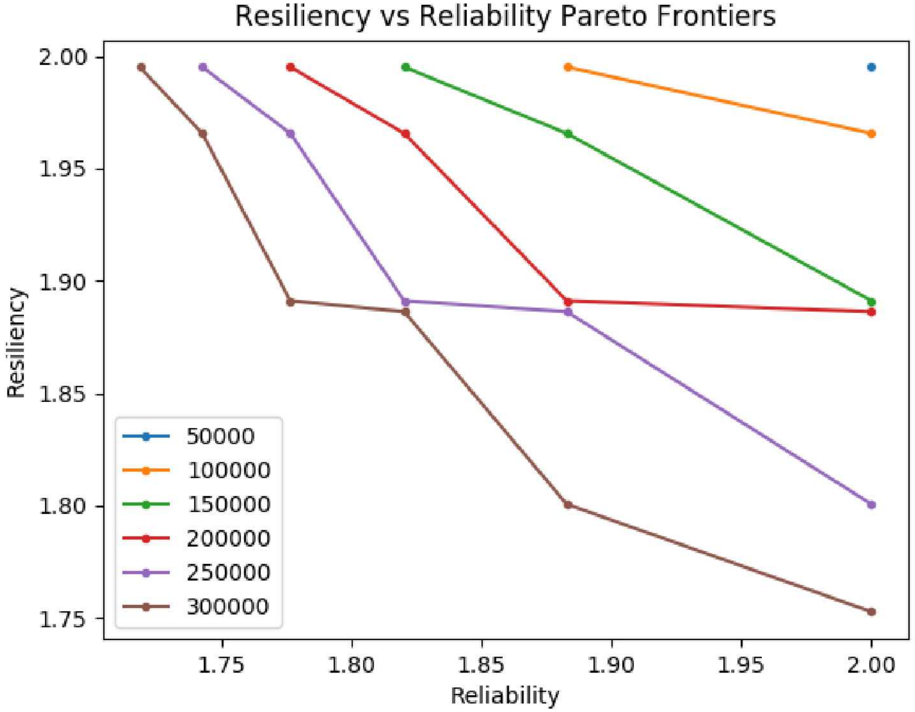


The improvement in reliability at budget increases. The optimal investments are chosen for each budget



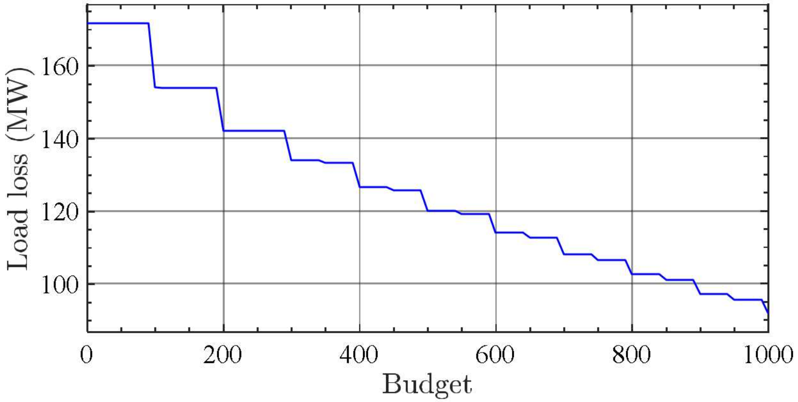
Pareto frontiers of weighting SAIDI or SAIFI more. Whether you weight SAIDI (duration) more or SAIFI (frequency of events) more, the results are similar.

Co-op results on IEEE RTS-96 system

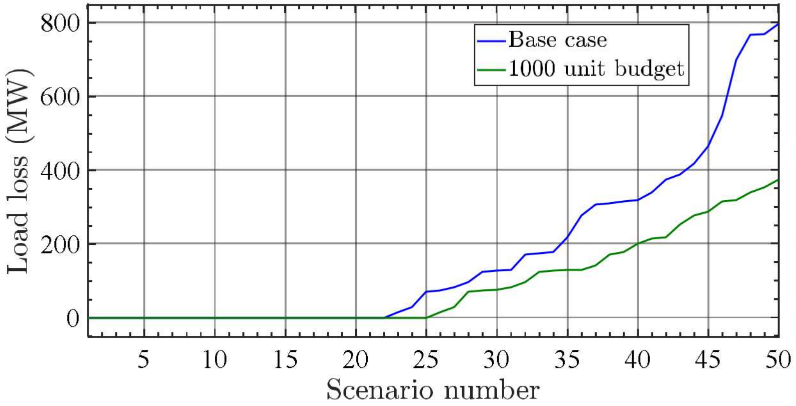


Pareto frontiers weighting Reliability vs. Resiliency.

Basic Resilience results on IEEE RTS-96 system



The expected loss of load from 50 storm scenarios vs. the investment budget



The loss of load per scenario without investments and with an investment of 1000 units

Conclusion

- Inform utilities and their stakeholders, DHS, DOE, and policy makers of those cost effective infrastructure investment decisions that simultaneously improve both reliability and resilience.

- Inhibit impacts to resilience at the expense of reliability or vice versa.

- Characterize tradeoffs between resiliency and reliability, for given infrastructure investment decisions.

- Aid utilities in formulating rate recovery cases to fund investments by quantifying both reliability and resilience impacts of proposed investments.

Future Work

- Elicit feedback from utilities, RTO's, and/or ISO's to understand how our models can be used and modified.

- Try different reliability assumptions on calculating duration and number of customers affected

- Research techniques for scaling resiliency model.

Thank You

- Questions?