Dispatch of Mobile Power Sources for Enhanced Grid Resilience using Ensemble Hurricane Forecasts

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Motivation: Hurricanes & Grid Vulnerability

The Problem

- **1,542 major power outages** (2000–2021) from extreme weather, each affecting $\geq$50,000 customers
- Grid hardening: slow, expensive, multi-stakeholder
- Forecast uncertainty makes pre-storm decisions hard

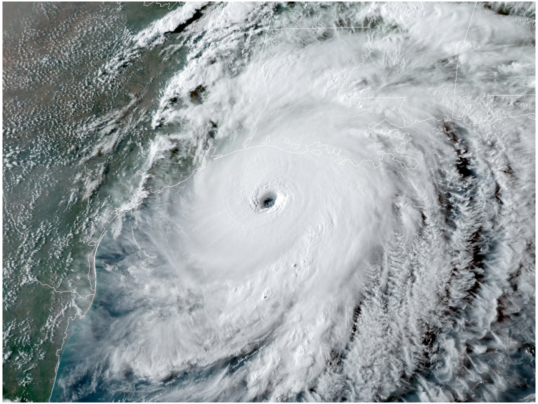

Figure: Satellite image of hurricane Laura

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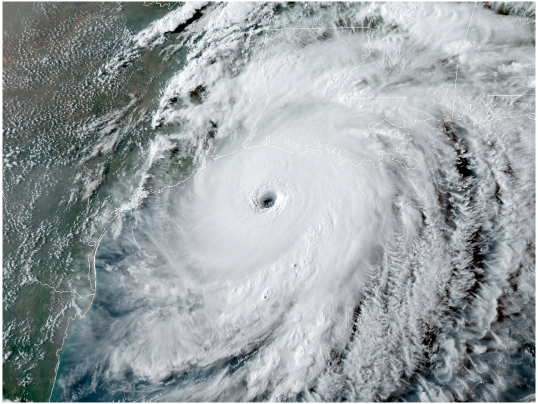
Opportunity

- NOAA issues ensemble hurricane forecasts every 6 hours
- *Can we exploit ensemble forecasts to minimize outages?*



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Mobile Power Sources (MPS)

Two types of MPS

- **Mobile Energy Storage Systems (MESS)**
  - Truck-mounted battery packs
  - Can *inject or absorb* power
  - 800 kWh unit deployed in the US, ≈ 30 households' daily consumption
- **Mobile Generators (MG)**
  - Diesel/gas generators on wheels
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Figure: MESS Truck

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Deployment Challenge

During the 2021 Texas winter storm, MPS units were used to aid recovery, however they were not proactively dispatched due to permitting delays and size constraints. Overcoming this could have prevented major blackouts

Figure: MESS Truck

Problem Statement

Given:

- Power network $(\mathcal{B}, \mathcal{L}, \mathcal{G})$ with DC power flow physics
- A fleet of MPS $\mathcal{M}$ with known locations, capacities, travel speeds
- Periodic ensemble hurricane forecasts from NOAA
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- Generator production and line transmission at each stage
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Information flow	Decisions
Stage 1 Anticipatory (before storm)	MPS placement, grid state

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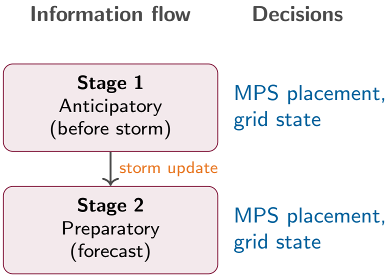

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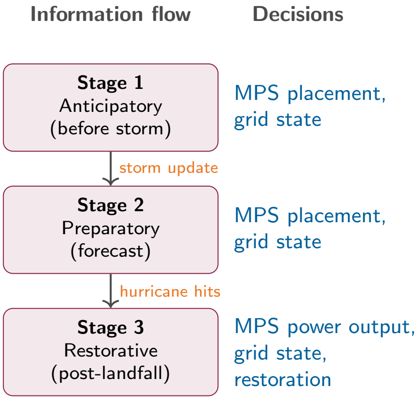

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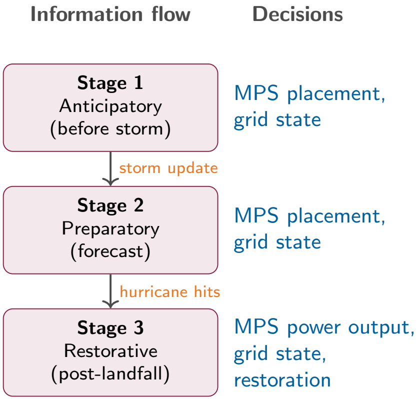

Decisions in Stage 1 constrain Stages 2 & 3 via ramping limits and MPS positions

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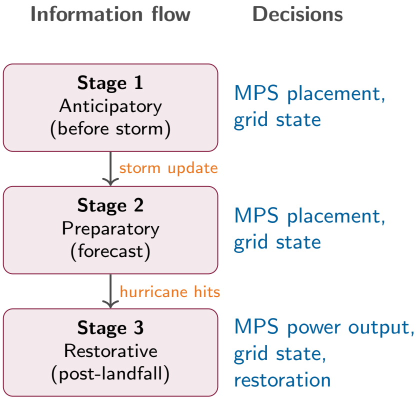
Objective:

Minimize expected load shed + over-production costs across all damage scenarios



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Related Work

Stochastic programming for grid resilience

- **Bynum et al. (2021)**: proactive redispatch + line hardening
- **Wang et al. (2022)**: 3-stage SP for integrated electricity & gas networks under hurricanes
- **Zhang et al. (2022)**: MDP + approx. dynamic programming for security-constrained UC under hurricanes

Rolling-horizon frameworks

- **Yao et al. (2019)**: rolling horizon for grid management under uncertainty

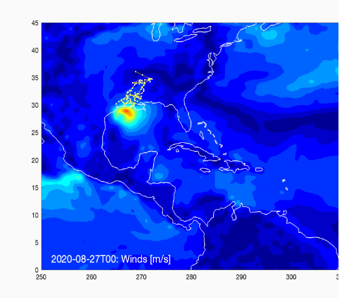
Mobile power sources

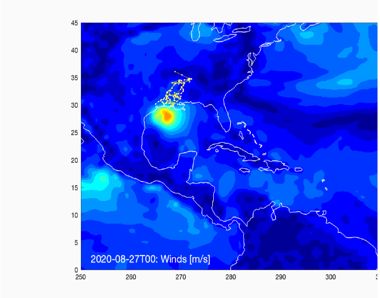
- **Abdeltawab & Mohamed (2019)**: MESS dispatch formulation
- **Zhao et al. (2024)**: incorporate MESS in a restoration framework

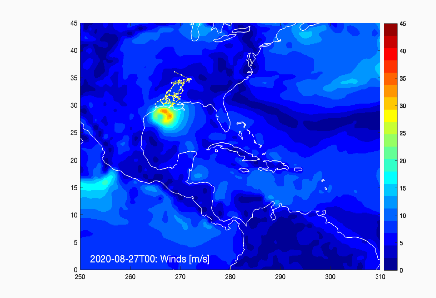
Gap this work fills

No existing work jointly addresses **ensemble forecasts** + **MPS routing** + **co-optimized restoration** + **rolling-horizon** re-optimization

Ensemble Hurricane Forecasts & Fragility Curves

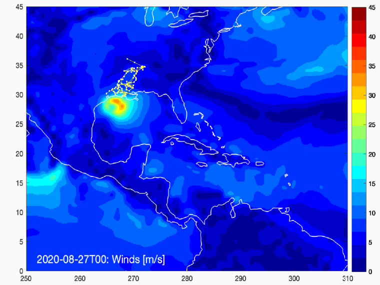






Ensemble Hurricane Forecasts & Fragility Curves

- **Generate N_ℓ points** along each transmission line, evenly spaced



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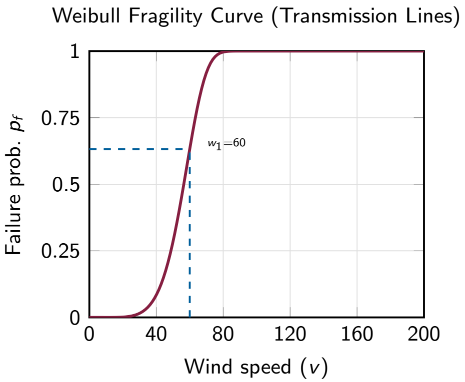
- **Generate N_ℓ points** along each transmission line, evenly spaced
- **Apply Weibull fragility curve** to convert local wind speed $V_{\ell,k}$ to a local failure probability:

$$P_{\ell,k}^{\text{fail}} = 1 - \exp\left\{-\left(\frac{V_{\ell,k}}{w_1}\right)^{w_2}\right\}$$



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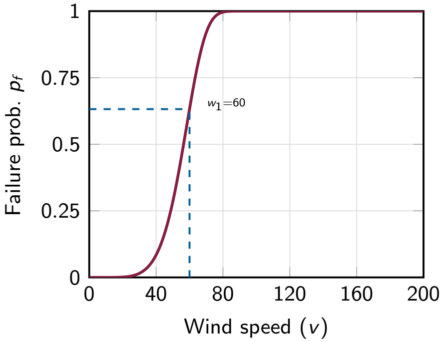
Weibull Fragility Curve (Transmission Lines)



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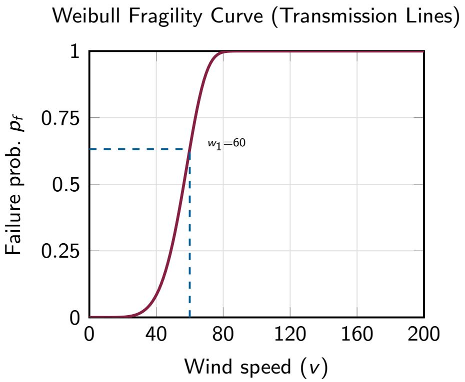
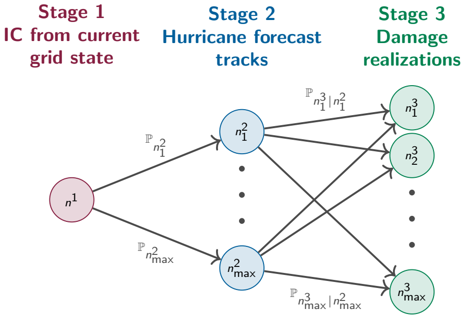
- Take the maximum over the forecast horizon, yielding one scalar per line per ensemble member



MSSP Structure: Three-Stage Scenario Tree

Challenge: Ensemble forecasts yield disjoint damage sets, which violates the Markovian assumption needed for SDDP



- Each node $n \in \mathcal{S}$ has time steps $\mathcal{T}_n$

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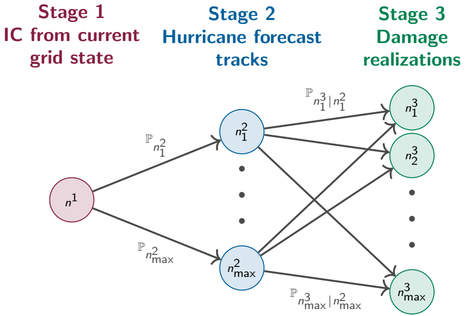
Our approach: Identify a common set of $n_{\max}^{S_3}$ damage scenarios across all Stage 2 forecasts



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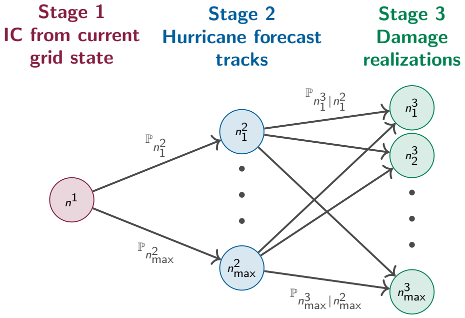

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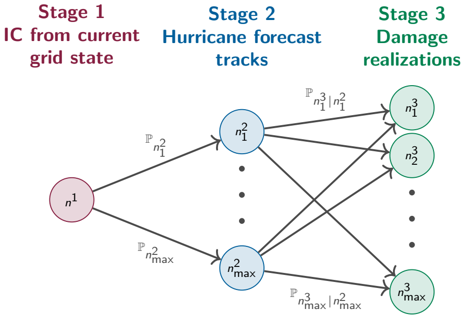

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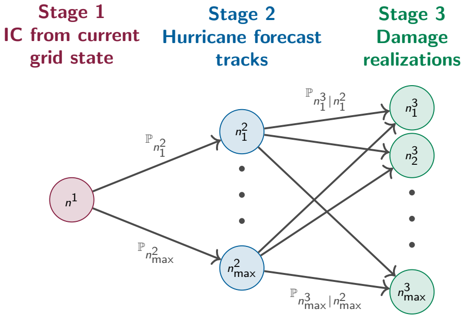

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Key idea

Restores Markovian structure, and makes sure model gets some information from each forecast

Formulation: DC Power Flow & Generator Limits

DC Power Flow Constraints (enforced at every $(n, t) \in \mathcal{S} \times \mathcal{T}_n$) $\underline{\cdot}$, $\overline{\cdot}$ = upper and lower limits:

Nodal balance

$$\sum_{g \in \mathcal{G}_i} p_g^{n,t} + \sum_{m \in \mathcal{M}} p_{m,i}^{n,t} = \sum_{ij \in \mathcal{L}} p_{ij}^{n,t} + \sum_{d \in \mathcal{D}_i} p_d^{n,t} y_d^{n,t} + \sum_{g \in \mathcal{G}_i} p_{g,\text{over}}^{n,t}$$

Generated Power + MPS Net power
= Line outflows + Load + Overproduction
$\forall\, i \in \mathcal{B},\ t \in \mathcal{T}_n,\ n \in \mathcal{S}$

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$s_{ij}^{n,t} = 1\ \forall n \notin \mathcal{S}_3$ (no damage before hurricane lands)

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Ramping limits (inter & intra stages)

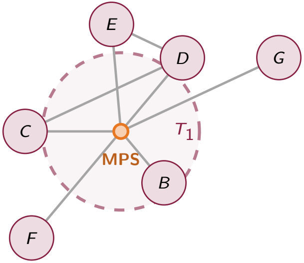
$$p_g^{a(n,t)} - \underline{r}_g \cdot \Delta t_n \le p_g^{n,t} \le p_g^{a(n,t)} + \overline{r}_g \cdot \Delta t_n$$

|Current power state -Previous power state|
$\le$ Ramping rate $\cdot \Delta t_n$
$\forall\, g \in \mathcal{G},\ t \in \mathcal{T}_n,\ n \in \mathcal{S}$

Formulation: MPS Routing & Reachability

Reachability: Can MPS m travel from i to j in time T?

$$R^T_{m,ij} = \begin{cases} 1 & \text{if } D_{ij}/v_m + t^p_{m,ij} \leq T \\ 0 & \text{otherwise} \end{cases}$$



Bus	T_1
B	1
C	0
D	0
E	0
F	0
G	0

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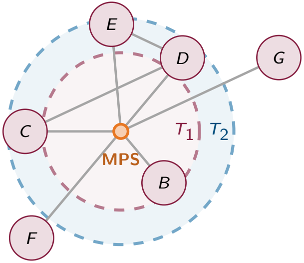

Bus	T_1	T_2
B	1	1
C	0	1
D	0	1
E	0	1
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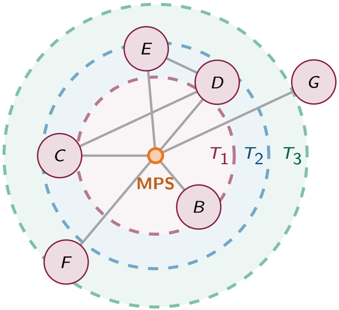

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Instead if MPS m is currently traveling between two buses:

$$t_{hk} = \min \left\{ \frac{D_{hi} + D_{ik}}{v_m} + t^p_{m,ik}, \frac{D_{hj} + D_{jk}}{v_m} + t^p_{m,jk} \right\}$$

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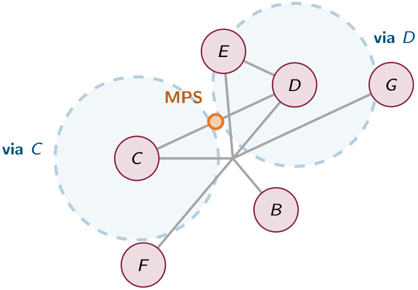

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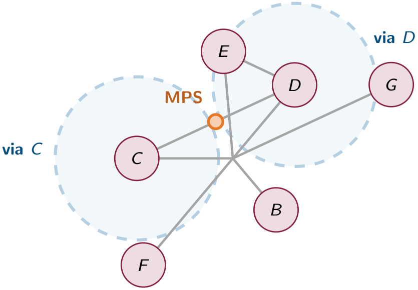
Stage 1 → 2 movement & **Stage 2 → 3 movement**:

- Have to move somewhere (current position included)
- Can only move to a reachable location

$q^{12}_{m,ij} = 1$ ($q^{23}_{m,ij} = 1$) if MPS m is moved from i to j between stage 1 & 2 (resp. 2 & 3), 0 otherwise



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Instead if MPS m is currently traveling between two buses:

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Connection capacity

$$\sum_{m \in \mathcal{M}} \sum_{i \in \mathcal{B}} q^{23}_{m,ij} \leq q_{\max,j} \quad \forall j \in \mathcal{B}$$

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$p^{n,t}_{m,j} = 0$ for $n \notin \mathcal{S}_3$ (MPS mobile during Stages 1 & 2)

Formulation: Damage & Restoration (Stage 3)

Line health evolution (restorative action $x_{ij}^{n,t}$):

$$z_{ij}^{n,t} = z_{ij}^{a(n,t)} + x_{ij}^{a(n,t)}, \quad 0 \leq x_{ij}^{n,t} \leq x_{ij}^{\max}, \quad z_{ij}^{n,t} \in [0,1]$$

Health status increases by restorative action

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Restorative budget per time step:

$$\sum_{ij \in \mathcal{L}} \frac{x_{ij}^{n,t}}{x_{ij}^{\max}} \leq b \quad \forall t \in \mathcal{T}_n, \; n \in \mathcal{S}_3$$

How many power lines can be repaired at once

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How many power lines can be repaired at once

Key idea

Proactively anticipating damage in Stage 3 allows Stages 1 & 2 decisions to hedge against the most damaging scenarios

Formulation: Objective Function

$$\min \underbrace{\sum_{n\in\mathcal{S}} \mathbb{P}_n \sum_{t\in\mathcal{T}_n} \sum_{g\in\mathcal{G}} c_g^{n,t}\, p_{g,\text{over}}^{n,t}}_{\text{Expected overproduction cost}} + \underbrace{\sum_{n\in\mathcal{S}} \mathbb{P}_n \sum_{t\in\mathcal{T}_n} \sum_{d\in\mathcal{D}} (1 - y_d^{n,t})\, p_d^{n,t}}_{\text{Expected load shed}}$$

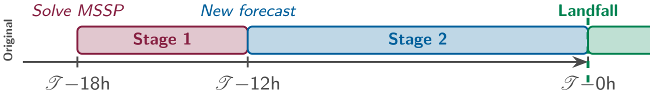
subject to: DC power flow, ramping, MPS routing, restoration

Design Rationale

- Stages 1 & 2: no damage yet, only overproduction costs
- Stage 3: hurricane hits, minimize loadshed
- Ramping and MPS placement links stages, early decisions matter for later recovery
- MPS routing is a decision that needs to be made before uncertainty resolves

Shrinking-Horizon Framework

1. At $\mathscr{T}-18$h: receive first ensemble; solve MSSP; enact Stage 1 policy



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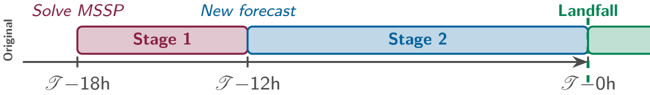

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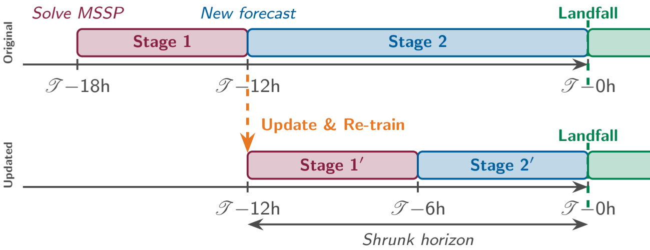

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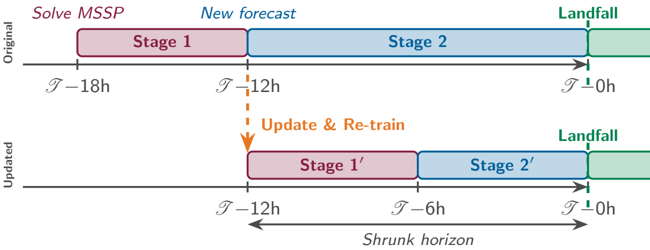

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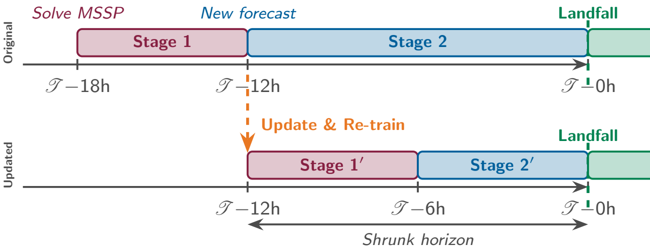

Benefit of this approach

This allows the model to make decisions with current information, and take corrective action as new data is received

Case Study Setup

IEEE Test Systems (geolocated to U.S. Gulf Coast)

- **IEEE-39 bus**: 10 generators, 46 lines, 21 loads (New England system, translated 11.2S, 21W)
- Tested against **Hurricane Laura (2020)**, a Category 5 Atlantic hurricane

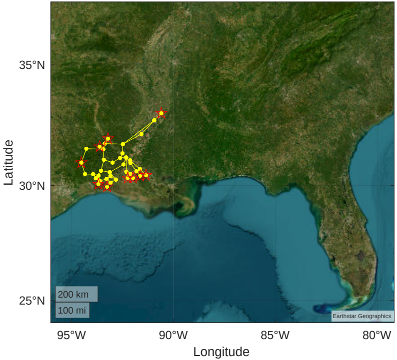

Figure: IEEE 39 Bus localized to the Gulf of Mexico

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- Virginia Tech OWL Cluster, single thread, 96GB RAM
- We used a single timestep in the first & second stage, and 12 timesteps in the third stage
- The restoration budget is equivalent to 1 line per timestep
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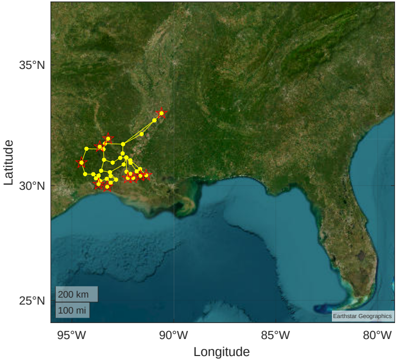

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Benchmarks

1. **Wait-and-see**: no action until damage occurs, MESS stay at initial position
2. **Mean forecast**: 2 stage model with single (mean) forecast
3. **Full MSSP**: full ensemble + shrinking horizon

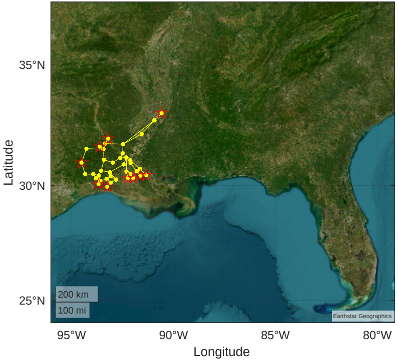

Figure: IEEE 39 Bus localized to the Gulf of Mexico

Results: Load Shed Reduction, MSSP vs. Wait-and-see (IEEE-39 Bus)

- Tested 5,000 samples, with random forecasts and damage scenarios

Key findings

- ≈2% average reduction in total cost
- Full MSSP approaches outperform wait-and-see

Scalability

IEEE-39 bus solved on a single core.
Solution time of 5.2h for MSSP.

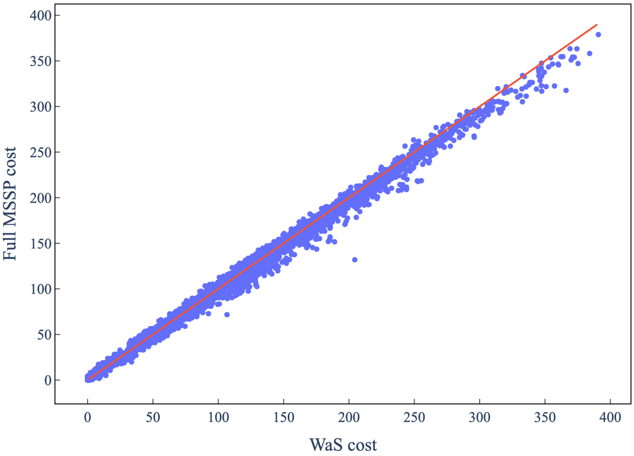

Figure: Pairs of (MSSP, WaS) OOS results (zoomed)

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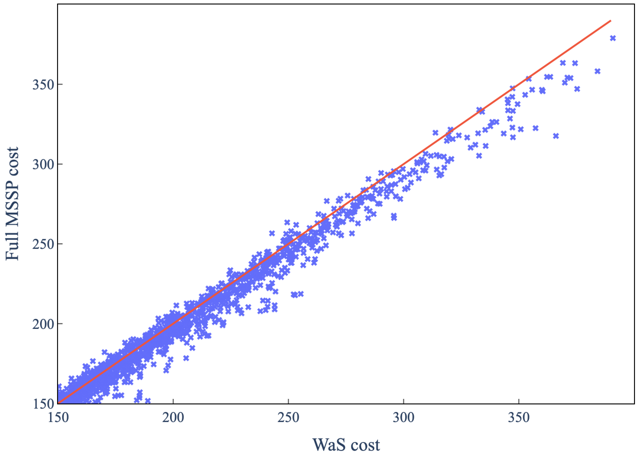

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Results: Load Shed Reduction, MSSP vs. Mean-track (IEEE-39 Bus)

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Key findings

- ≈1.5% average reduction in total cost
- Full ensemble MSSP consistently outperforms single mean-track approach
- Both MSSP approaches outperform wait-and-see

Scalability

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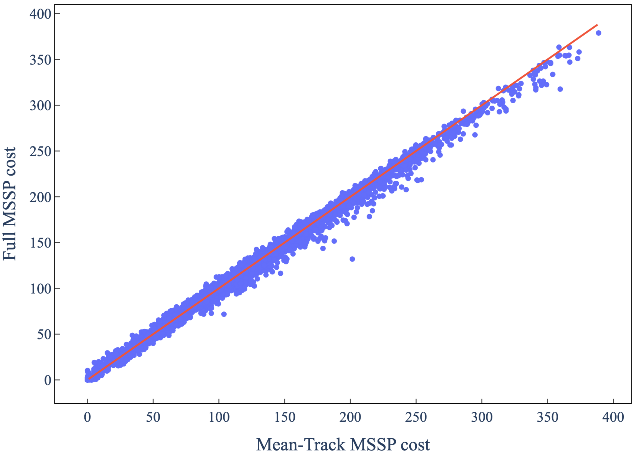
Solution times:

- Full MSSP: 5.2h
- Mean-track MSSP: 3.5h



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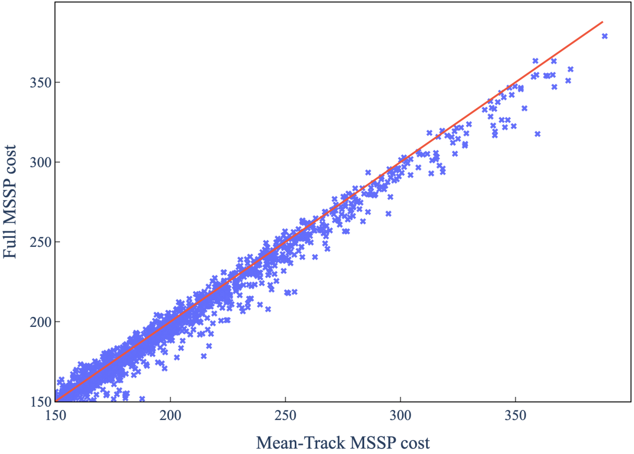

Figure: Pairs of (MSSP, Mean-track MSSP) OOS results

Summary & Conclusions

Contributions

1. **Three-stage multi-period MSSP** that integrates ensemble hurricane forecasts, MPS dispatch, and grid restoration in a unified framework
2. **Data-driven scenario reduction** enabling Markov-chain SDDP
3. **Co-optimization** of MPS routing and restoration; early decisions hedge against the worst damage scenarios
4. **Shrinking-horizon** framework enables real-time re-optimization as forecasts update
5. **Scalable**: Solved on a single core

Ongoing & Future Work

- Test on IEEE-118 bus and larger grids
- AC power flow
- Adaptive forecast weighting (ECMWF + NOAA)

Thank You!

Questions?

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Acknowledgements

Los Alamos Laboratory LDRD Program

LANL Center for Nonlinear Studies

Backup: Full Optimization Model Summary

Decision Variables (per node n, time t):

$p_g^{n,t}$	generator output
$p_{g,\text{over}}^{n,t}$	overgeneration (slack)
$\theta_i^{n,t}$	voltage phase angle
$y_d^{n,t}$	fraction of load served
$p_{m,j}^{n,t}$	MPS power injection
$E_m^{n,t}$	MPS energy / SoC
$q_{m,hi}^{12}$, $q_{m,ij}^{23}$	MPS routing (binary)
$z_{ij}^{n,t}$	health fraction
$s_{ij}^{n,t}$	binary health status
$x_{ij}^{n,t}$	restorative actions

Constraint Groups:

(1) DC nodal balance
(2) Generator output limits
(3) Line flow limits
(4) Phase angle / Kirchhoff
(5) Generator ramping (all stages)
(6) MPS reachability (Stage 1→2)
(7) MPS reachability (Stage 2→3)
(8) MPS power & energy (Stage 3)
(9) Health evolution (Stage 3)
(10) Binary health linking
(11) Restorative budget

Backup: Key Notation

Sets

$\mathcal{B}$	Buses
$\mathcal{D}_i$	Loads at bus i
$\mathcal{G}_i$, $\mathcal{G}$	Generators at bus i; all gens
$\mathcal{L}$	Transmission lines
$\mathcal{M}$	Mobile Power Sources
$\mathcal{S}$, $\mathcal{S}_j$	Scenario tree nodes; stage j nodes
$\mathcal{T}_n$	Time steps of node n

Key Parameters

$\mathbb{P}_n$	Probability of node n
b_{ij}	Line susceptance
v_m, D_{ij}	MPS speed; inter-bus distance
$t^p_{m,ij}$	Permit time for MPS m
E_m	MPS energy capacity
b	Restorative budget per step

Assumptions

- DC power flow (linear approximation)
- Full observability of grid model & fragility curves
- All non-damaged generators cooperate
- MPS travel times known a-priori (road network + permitting)
- No generator damage before Stage 3
- Integrality of restoration relaxed for tractability

Solver: SDDP.jl (Julia) via JuMP
Algorithm: Markov-chain SDDP

Backup: Generator Ramping Parameters (ARPA-E GO)

- IEEE test cases lack ramping data, so it was derived from **ARPA-E GO Challenge 3**
- Five systems: 73, 617, 1576, 2000, 4224 buses
- Ramp-up ≈ ramp-down (symmetric): $\underline{r}_g^{n,t} = \overline{r}_g^{n,t}$
- Piecewise linear depending on max capacity:

$$\overline{r}_g^{n,t} = \begin{cases} \overline{p}_g \cdot T^{n,t} & \overline{p}_g \leq 4\,\mathrm{MW} \\ 0.15\,\overline{p}_g \cdot T^{n,t} & \overline{p}_g > 4\,\mathrm{MW} \end{cases}$$

- $T^{n,t}$: duration (hours) from (n, t) to successor node

Backup: Mean-track MSSP Scenario Tree