IOWA STATE UNIVERSITY

Department of Industrial and Manufacturing Systems Engineering

Enhancing Resilience of the Electric Power Sector after Hurricane Sandy

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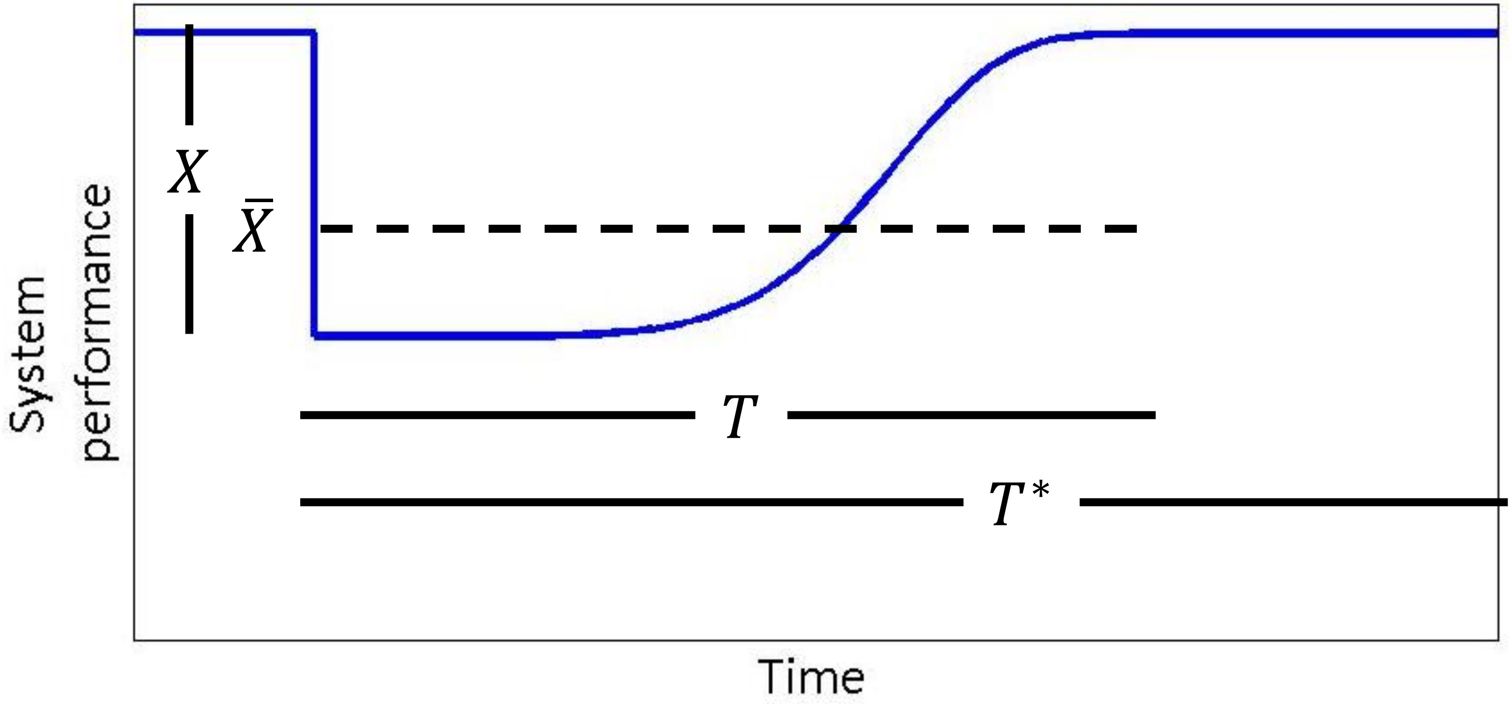
Quantifying disaster resilience

$$R_*(\bar{X}, T) = 1 - \frac{\bar{X}T}{T^*}$$



Zobel, C.W. (2014). Quantitatively representing nonlinear disaster recovery. *Decision Sciences*, 45(6), 687-710.

Research questions

1. How should a decision maker allocate resources between reducing loss and decreasing time in order to maximize resilience?
2. Does the optimal decision change when there is uncertainty?
3. How can this theoretical model be applied to a enhancing the resilience of electric power systems?

Resource allocation model

$$R_*(\bar{X}, T) = 1 - \frac{\bar{X}T}{T^*}$$

Factor as a function of resource allocation decision

maximize $R_*\left(\bar{X}(z_{\bar{X}}), T(z_T)\right)$

minimize $\bar{X}(z_{\bar{X}}) * T(z_T)$

subject to $z_{\bar{X}} + z_T \leq Z$

Budget

$z_{\bar{X}}, z_T \geq 0$

Allocation functions

- $\bar{X}(z_{\bar{X}})$ and $T(z_T)$ describe ability to allocate resources to reduce each factor of resilience
- Requirements
    - Factor should decrease as more resources are allocated: $\frac{d\bar{X}}{dz_{\bar{X}}}$ and $\frac{dT}{dz_T}$ are less than 0
    - Constant returns or marginal decreasing improvements as more resources are allocated: $\frac{d^2\bar{X}}{dz_{\bar{X}}^2}$ and $\frac{d^2T}{dz_T^2}$ are greater than or equal to 0

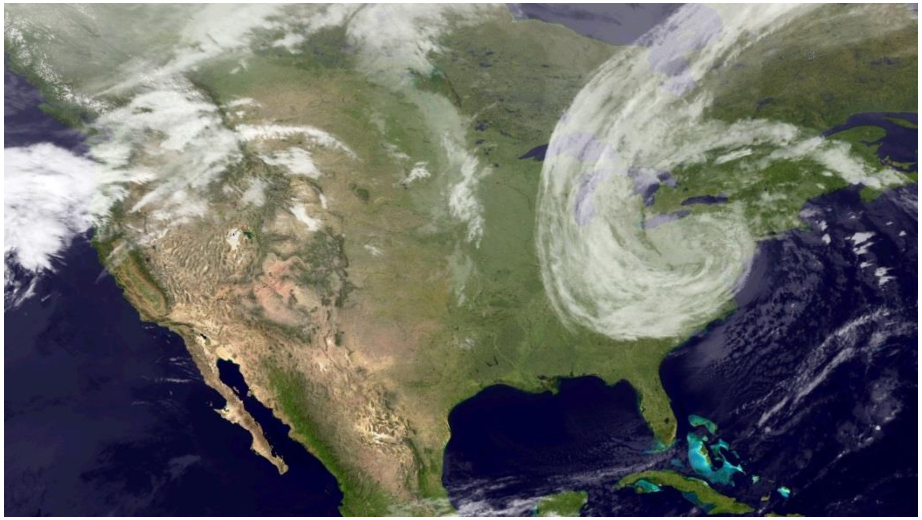
Model types

- Allocation functions
    1. Linear
    2. Exponential
    3. Quadratic
    4. Logarithmic

- Allocation under certainty
- Allocation under uncertainty (independence, dependence)
- Robust allocation

Superstorm Sandy

- October 2012: East coast of the U.S.
- ConEdison Electric Utility
  - 670,000 New York city customers without electricity
  - Approximately 1/5 of ConEdison’s customers
  - Duration: 13 days



ConEdison's Post-Sandy Plan

- $1 billion over 4 years to increase resilience of electric power network
- Hardening activities (reduce $\bar{X}$)
  - Trimming trees around power lines
  - Building higher flood plains
  - Backup power for substations
- Restoration activities (reduce T)
  - Smart-grid technologies
  - Preemptively shutting down steam plants
  - Deploying advance teams before the storm

Consolidated Edison Co. of New York. (2013). Post-Sandy enhancement plan. Orange and Rockland Utilities.

Model parameters

- From Zobel (2014) and Johnson (2005)

	Most likely	Minimum	Maximum
$\hat{X}$	0.073	0.030	0.22
$\hat{T}$	13	3	26

- Assume triangular distribution

Zobel, C.W. (2014). Quantitatively representing nonlinear disaster recovery. *Decision Sciences*, 45(6), 687-710.

Johnson, B.W. (2005). After the disaster: Utility restoration cost recovery. Report prepared for the Edison Electric Institute.

Model parameters

Effectiveness parameters for different allocation functions from

- Brown, R. (2009). Cost-benefit analysis of the deployment of utility infrastructure upgrades and storm hardening programs. Report prepared for the Public Utility Commission of Texas. Quanta Technology.
- Consolidated Edison Co. of New York. (2013). Post-Sandy enhancement plan. Orange and Rockland Utilities.
- Terruso, J., Baxter, C., & Carrom, E. (2012). Sandy recovery becomes national mission as countless workers come to N.J.'s aid. *The Star-Ledger* (Newark). November 11.

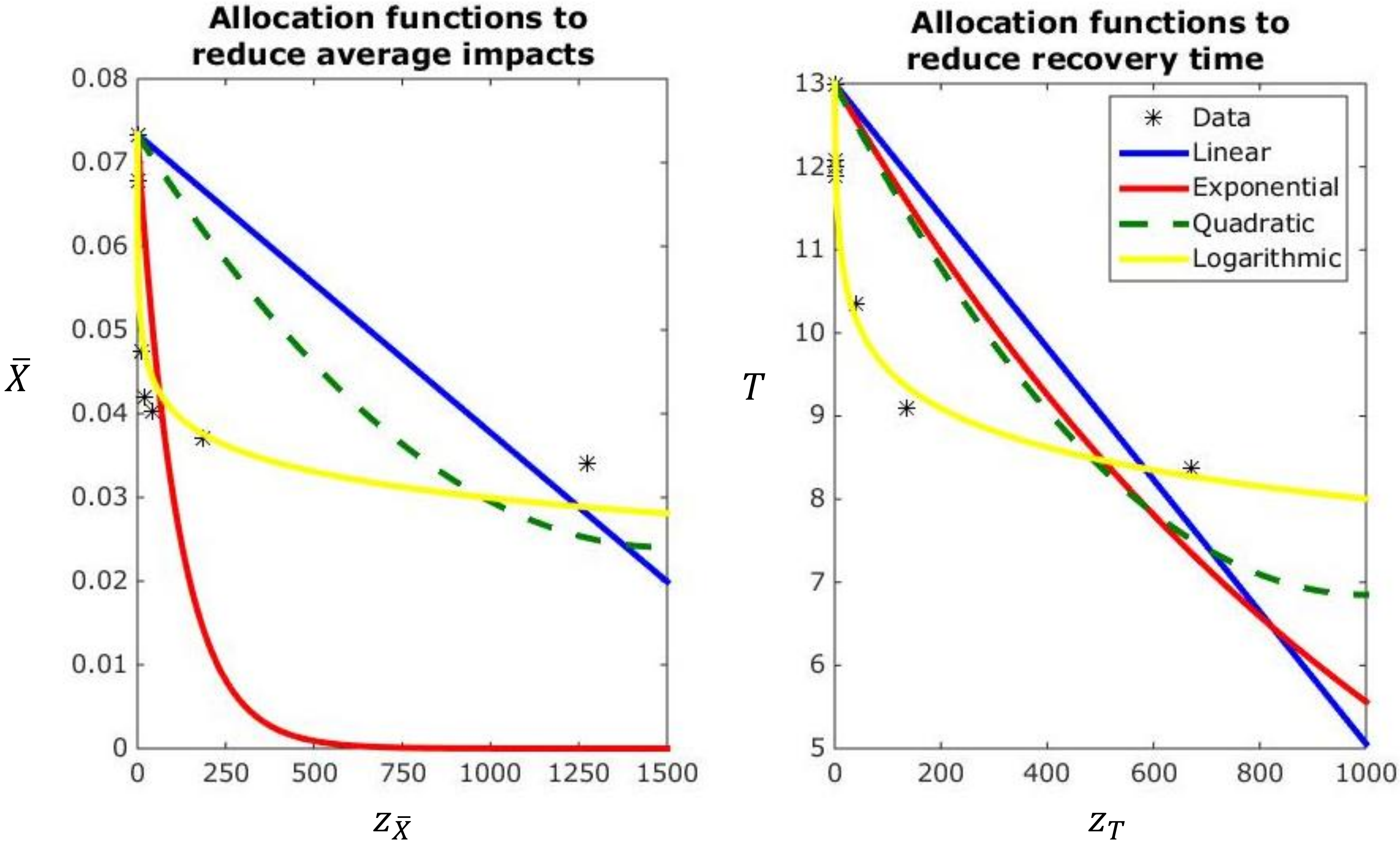
Costs and benefits of hardening

Activity	Cost ($ millions)	Benefits (percentage of reduced damage)	Benefit-cost ratio
Vegetation removal	1.3	7.6	5.8
Backup power substation	9.9	30.0	3.0
New substations	9.9	11.6	1.2
Ground-based inspection	21.8	4.0	0.18
Hardened distribution	145	8.0	0.055
Hardened transmission	1088	8.0	0.0074

Costs and benefits of recovery

Activity	Cost ($ millions)	Benefits (percentage of reduced recovery time)	Benefit-cost ratio
Deploy restoration teams	1.8	7.1	3.9
Adv. network monitoring	0.2	0.5	2.5
Automatic fault location	0.7	1.0	1.4
Distribution automation	37	13.0	0.35
Distributed generation penetration	96	12.0	0.13
Adv. metering infrastructure	537	8.0	0.015

Best fit for allocation functions



Optimal allocation (certainty)

Allocation function	Allocation to increase hardness ($ million)	Allocation to improve recovery ($ million)	Resilience	Average number of customers without power	Duration (days)
No efforts			0.96	232,000	13
Linear	0	1000	0.99	232,000	5.1
Exponential	1000	0	1.00	36	13
Quadratic	762	238	0.99	114,000	10.4
Logarithmic	648	352	0.99	101,000	8.7

Optimal allocation (uncertainty)

Allocation function	Allocation to increase hardness ($ million)	Allocation to improve recovery ($ million)	Expected resilience	Average number of customers without power	Average duration (days)
No efforts			0.94		
Linear	0	1000	0.97	337,000	4.9
Exponential	1000	0	1.000	2,308	14
Quadratic	556	444	0.99	60,418	9.1
Logarithmic	494	506	0.98	200,000	9.4

What if logarithmic is wrong?

Allocation function	Given optimal allocation of logarithmic function ($z_{\bar{X}}$ = \$648 and z_T = \$352 mil)			Optimal resilience	Average customers without power	Duration (days)
	Resilience	Average customers without power	Duration (days)			
Logarith	0.99	101,000	8.7			
Linear	0.98	159,000	10.2	0.99	232,000	5.1
Expon	1.00	36	13	1.00	36	13
Quadratic	0.99	114,000	10.4	0.99	101,000	8.7

Recommendations for ConEdison

- Logarithmic allocation function seems most appropriate
  - Approximates data well
  - Allocation performs well even if another function is correct
- Allocate between 50 and 65% of budget to reduce number of customers who lose power and 35 to 50% to improve recovery

Conclusions

- Assumptions impact optimal allocation
- Heuristics
  - Focus resources on small initial value and large effectiveness
  - Uncertainty: divide resources approximately equal manner if marginal benefits decrease rapidly
- Future work
  - Apply allocation model to specific projects
  - Resources can improve both factors simultaneously

MacKenzie, C.A., & Zobel, C.W. (2016). Allocating resources to enhance resilience, with application to the electric power network. *Risk Analysis* 36(4), 847-862.

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