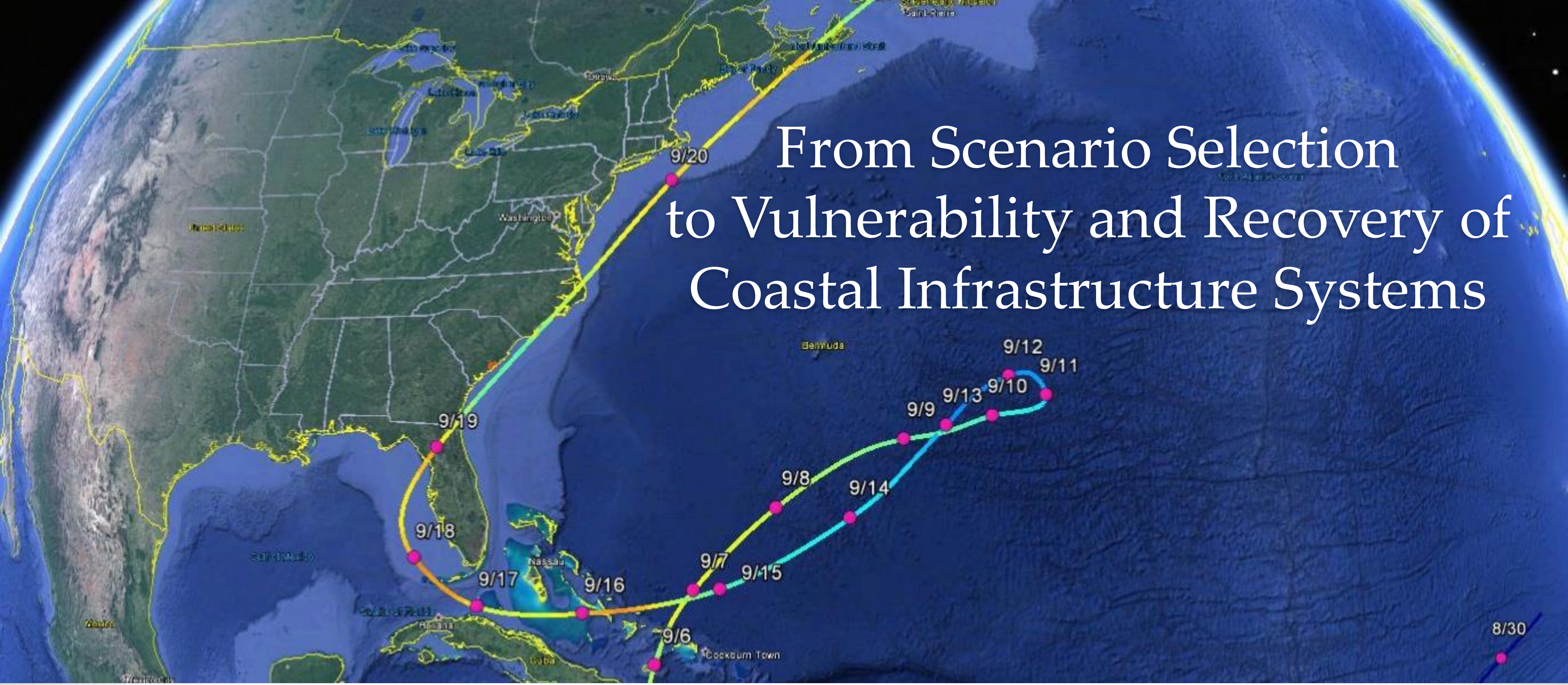
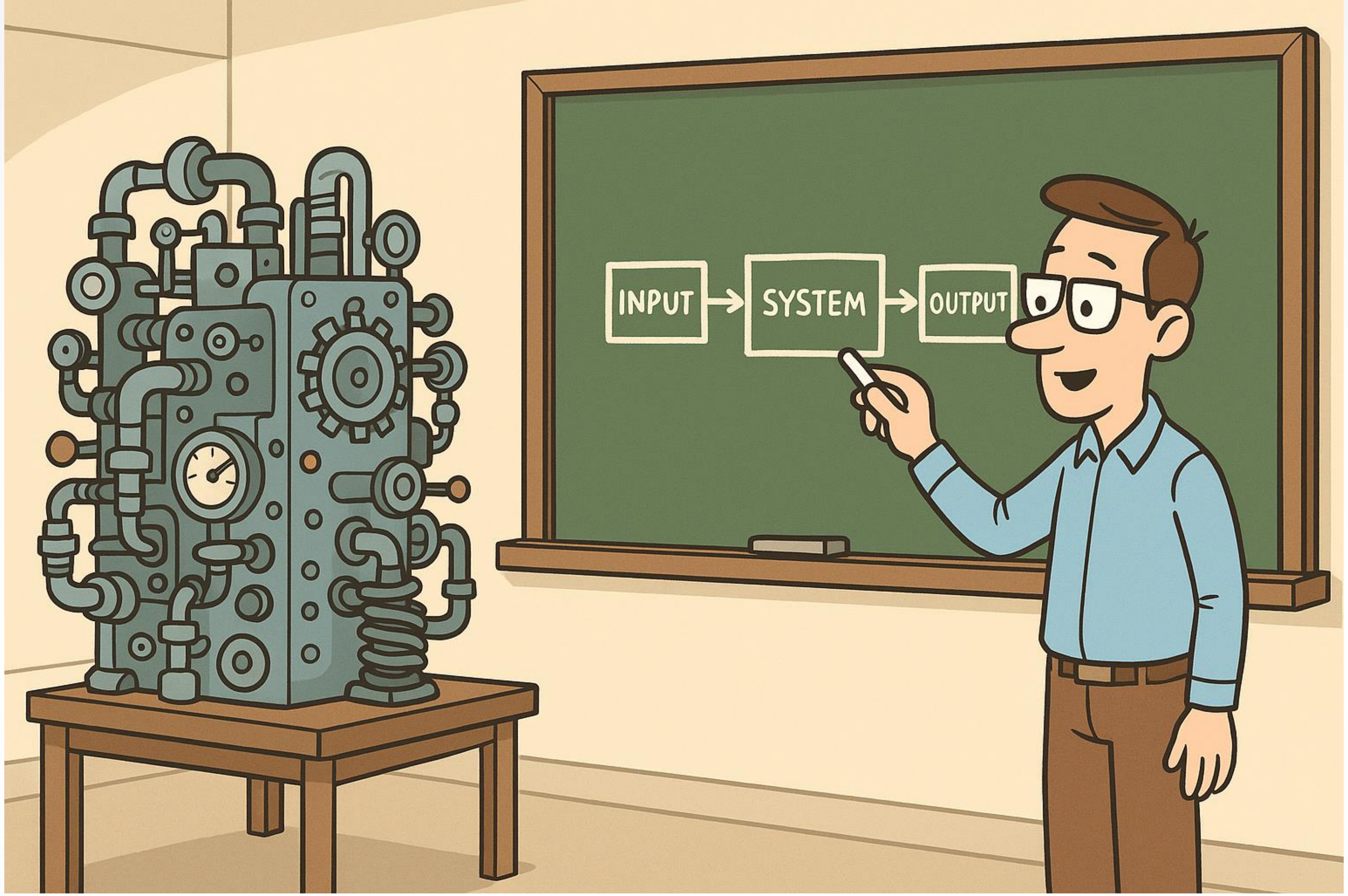
From Scenario Selection to Vulnerability and Recovery of Coastal Infrastructure Systems



Lehigh University
Center for Catastrophe Modeling and Resilience

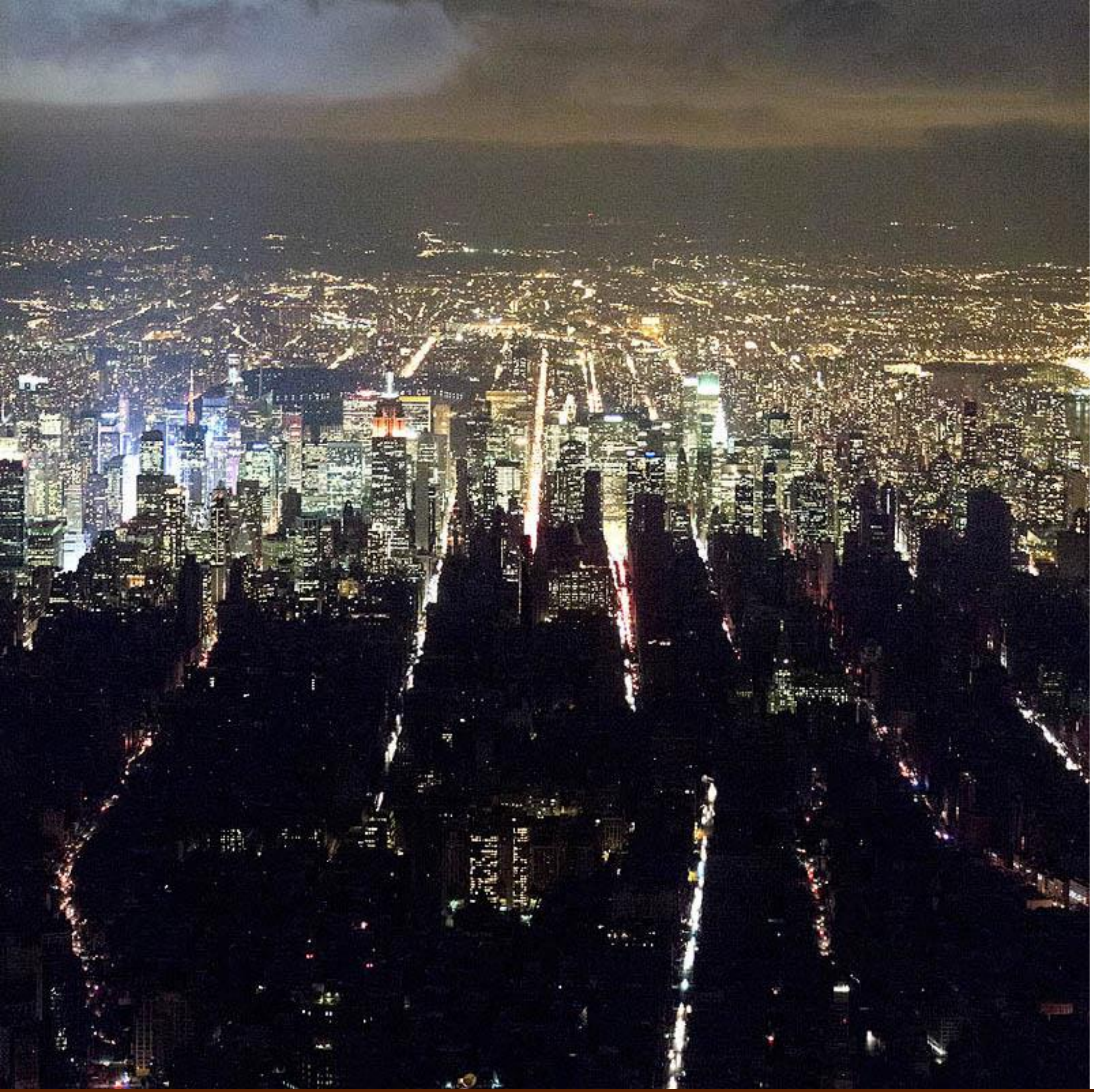
Paolo Bocchini

World Federation of Engineering Organization
June 12, 2025



«Engineering is the art of approximation»

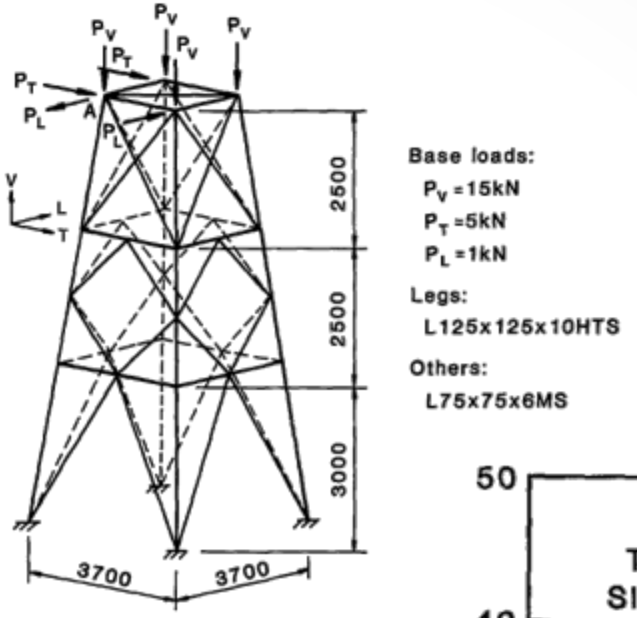
[Unknown Source]

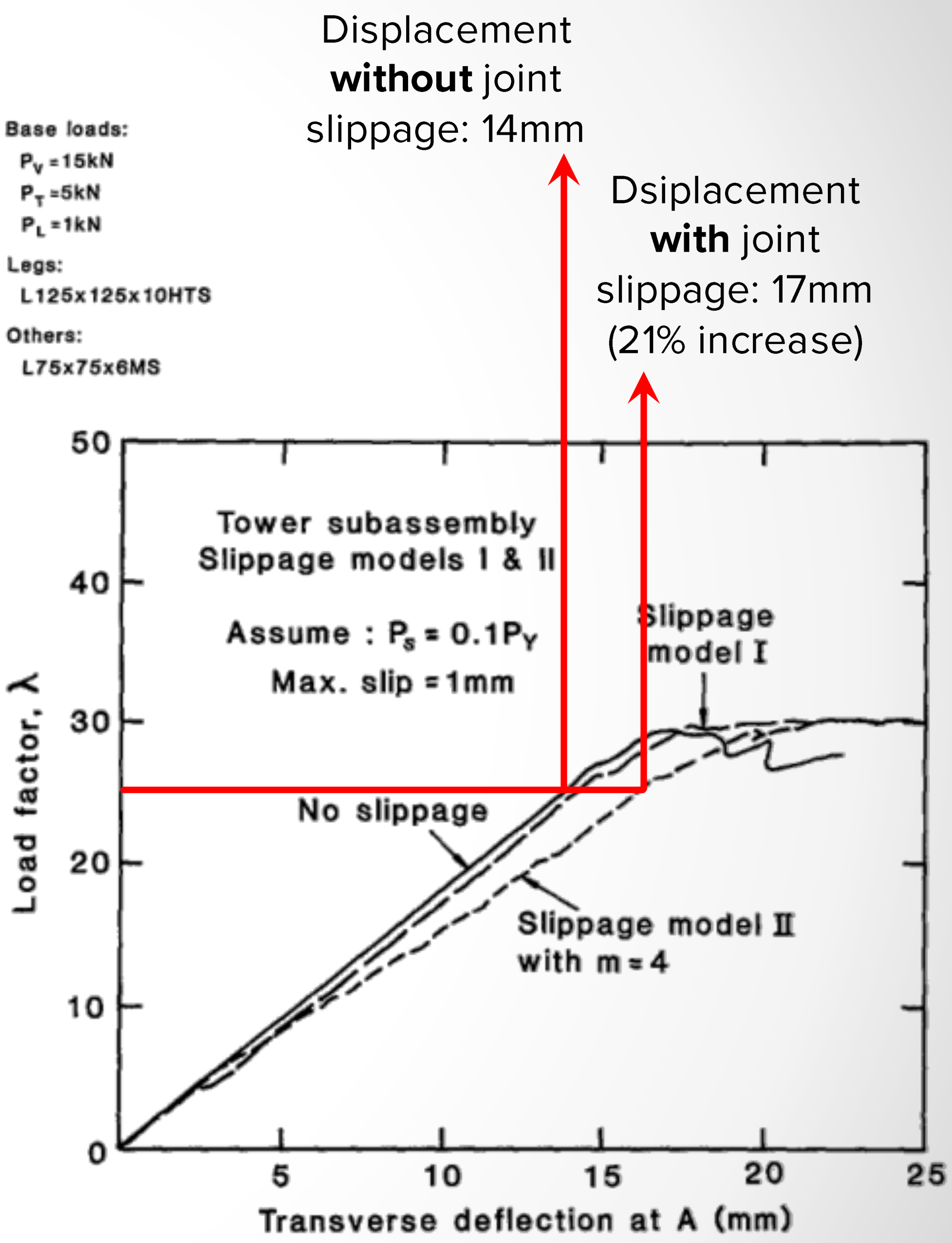


Functionality should be measured at the system level

Aerial view of New York City during the blackout caused by Hurricane Sandy, 2012

Loss of functionality may be caused by minute details





[Kitipornchai, Al-Bermani, & Peyrot. *Journal of Structural Engineering*, 1994.]

Multi-Scale Analysis… in Space, Time, and Probability

Size [m]

10^{5}

10^{4}

10^{3}

10^{2}

10^{1}

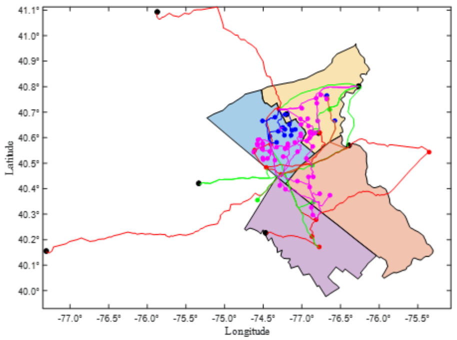
10^{0}

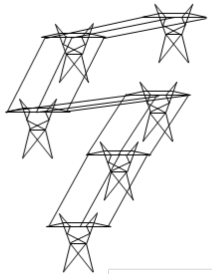
10^{-1}

10^{-2}

10^{-3}

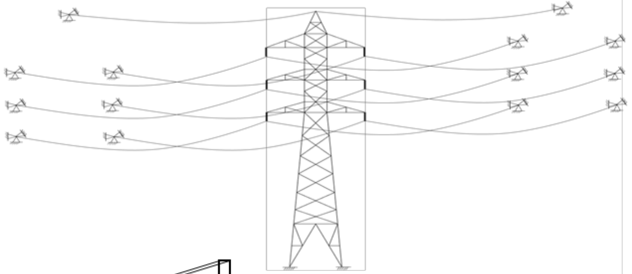
Power transmission networks

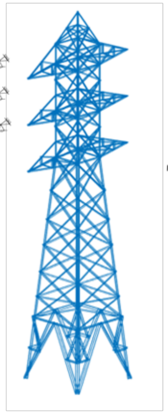




Transmission lines

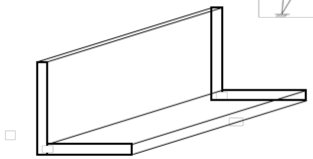
Conductor cables

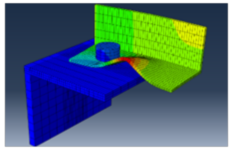




Transmission towers

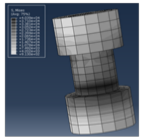
Angle members





Joint connections

Bolt



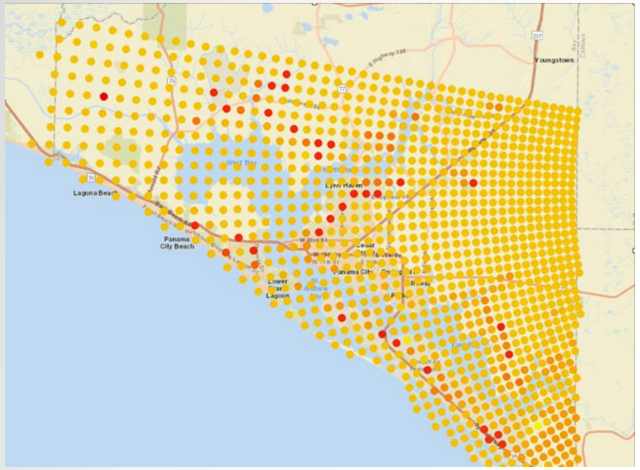
System analysis

Fragility analysis

Structural mechanics

Continuum mechanics

Topics of This Webinar

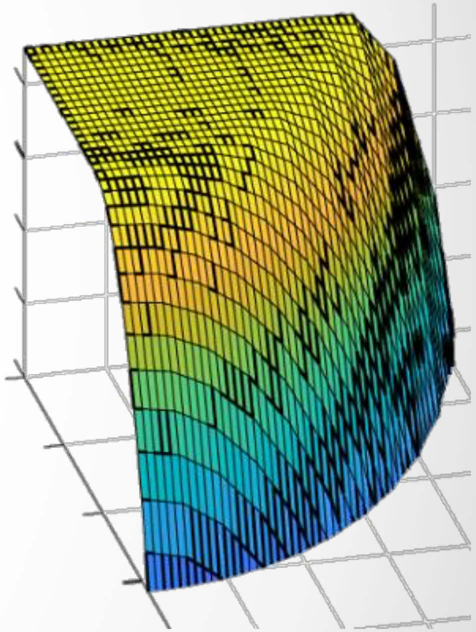


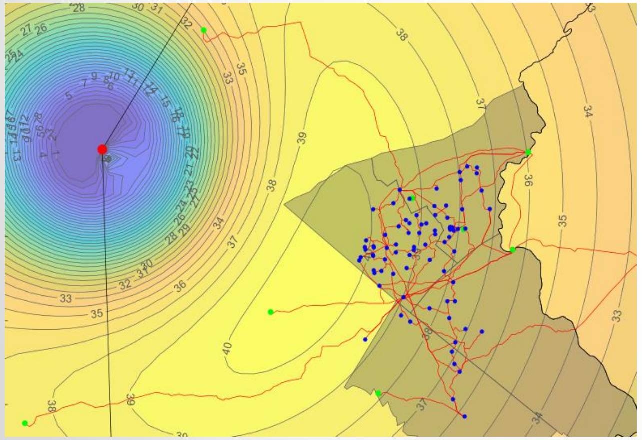
Approximation of the probability space: scenario selection

1

2

Approximation of the structural behavior: fragility models

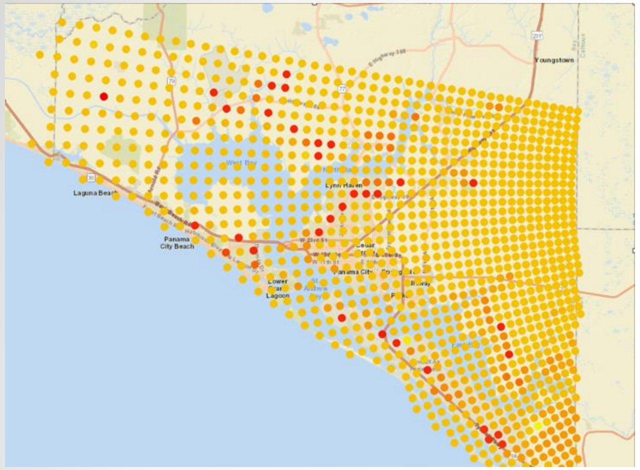




Approximation of the space and time domain: regional damage and recovery analysis

3

Topics of This Webinar

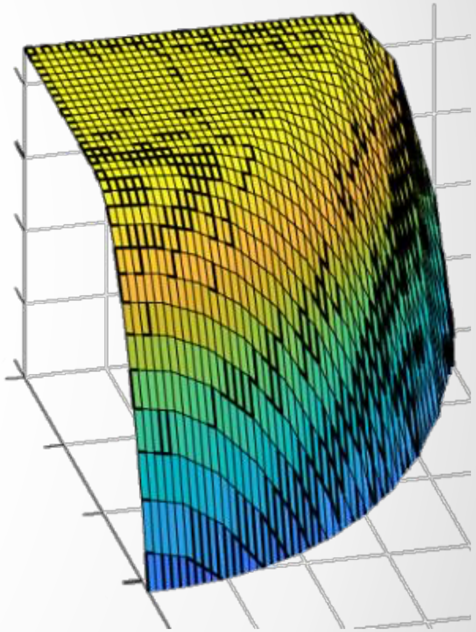


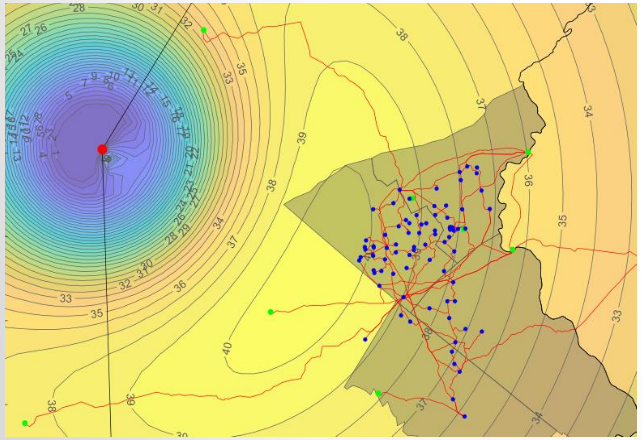
Approximation of the probability space: scenario selection

1

2

Approximation of the structural behavior: fragility models

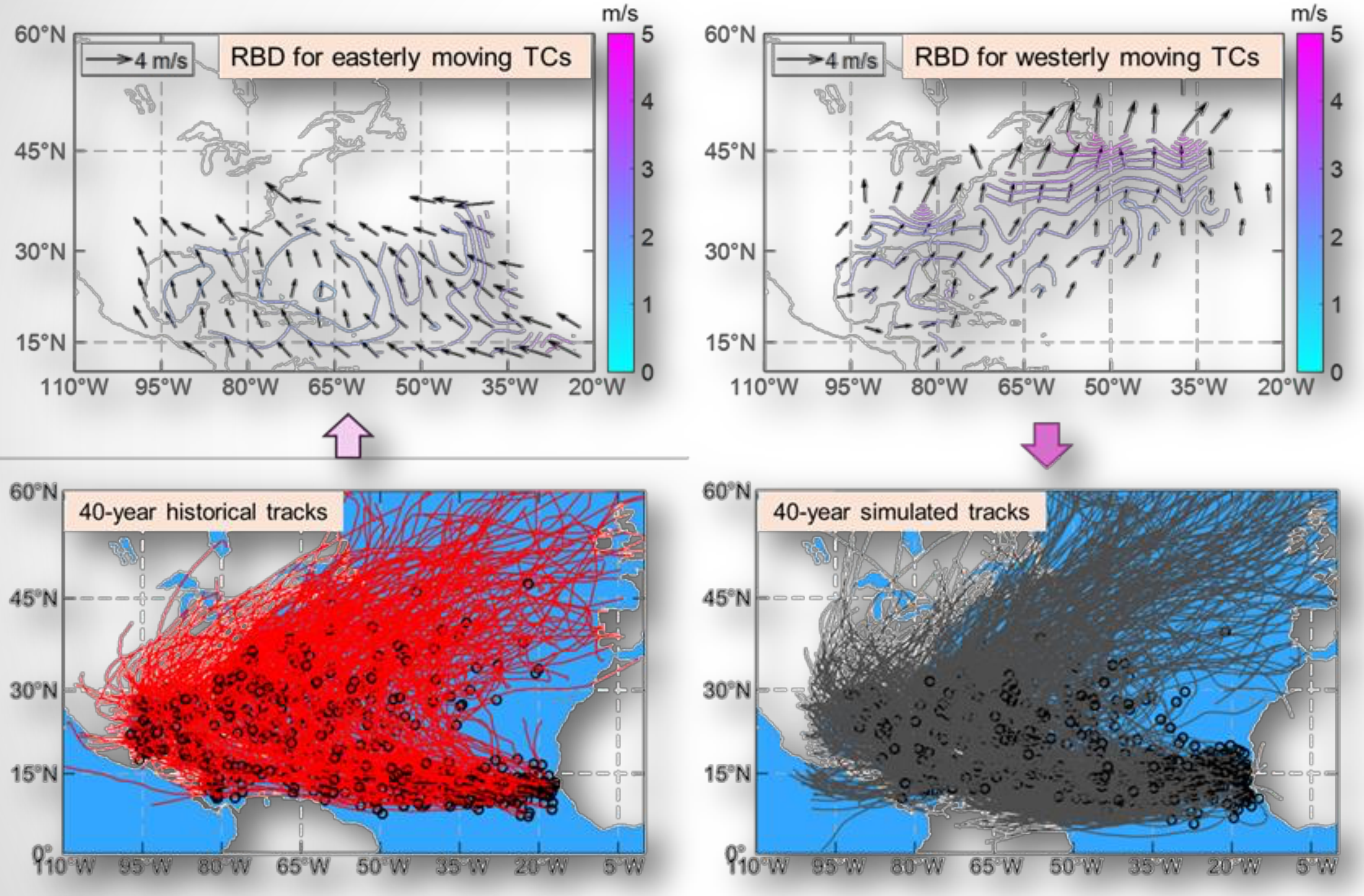




Approximation of the space and time domain: regional damage and recovery analysis

3

Hazard Model: E.g., Hurricane Simulation



[Sheng & Bocchini (2025a), An improved physics-based hurricane track model over the North Atlantic basin with its application for wind-hazard assessment. *Journal of Structural Engineering*, accepted for publication.]

[Sheng & Bocchini (2025b), Characterization and statistical modelling of tropical cyclone wind inflow angles for joint wind speed and direction hazard assessment. *Wind and Structures*, accepted for publication.]

Hazard Model

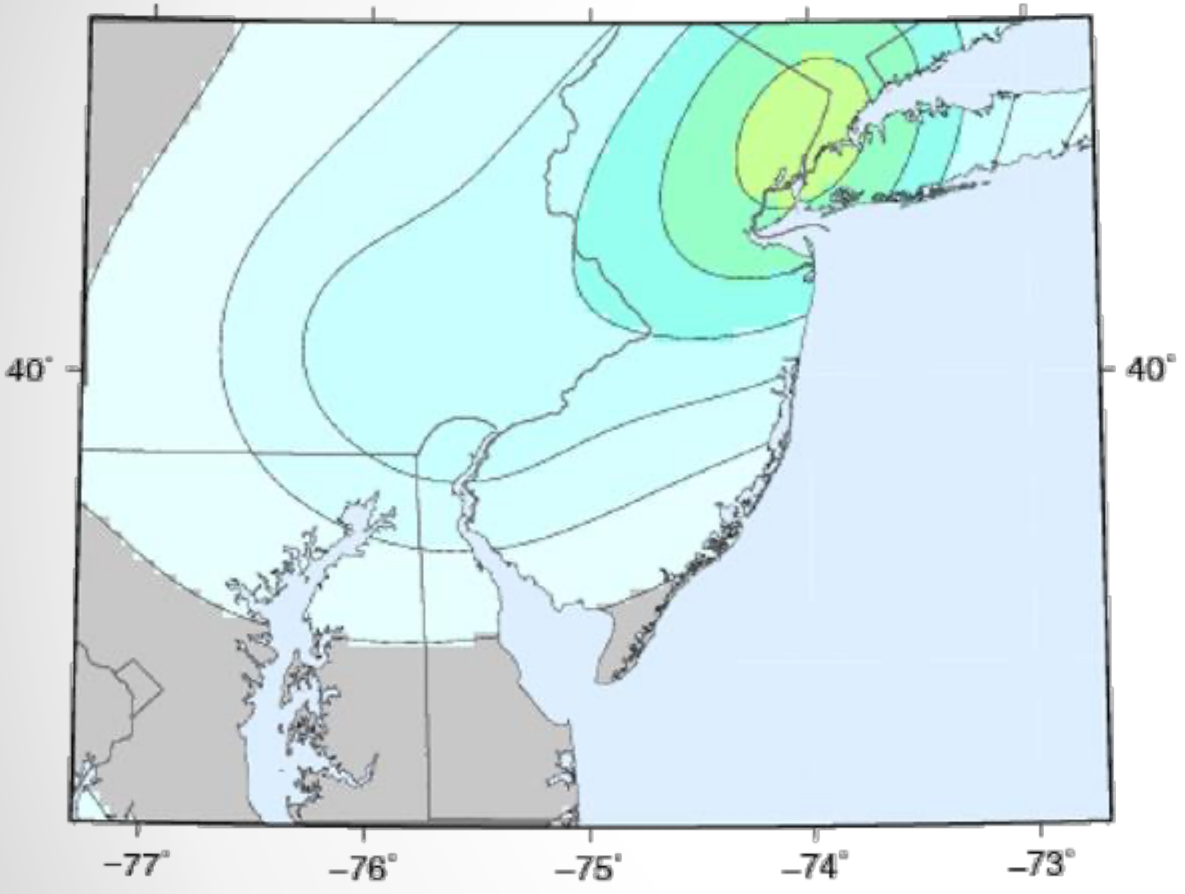
Scenario-based analysis

Use one or a small set of hurricane events and study how the system behaves

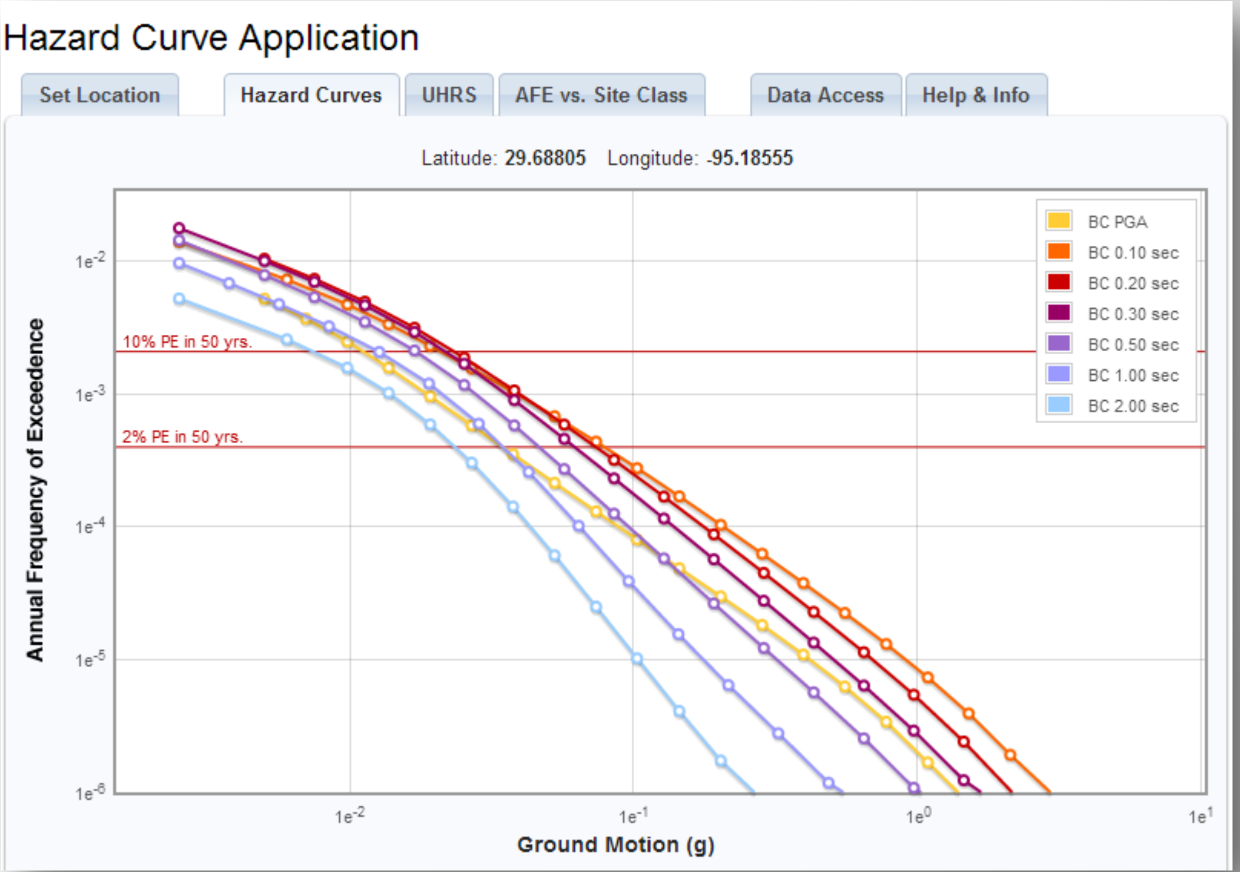
Probabilistic analysis

Study a large portfolio of events affecting the region, with the goal of capturing all the variability of possible events affecting the area.

Hazard Scenarios –Vs – Hazard Maps

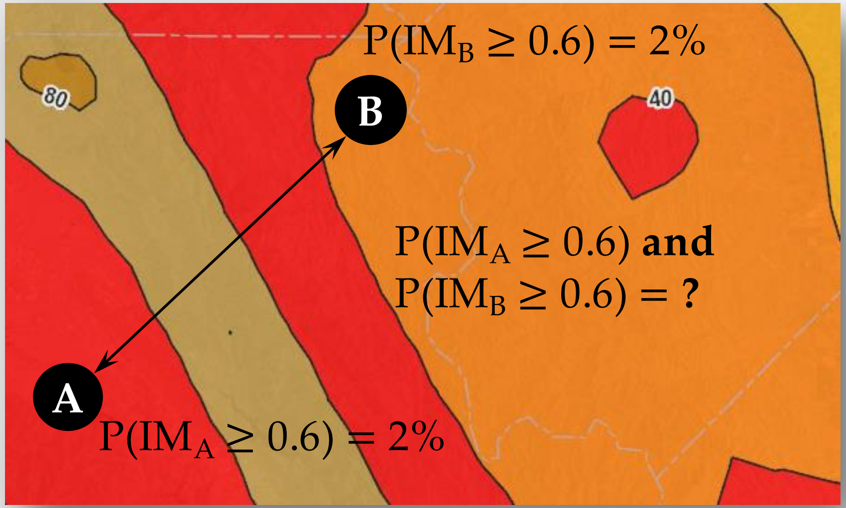


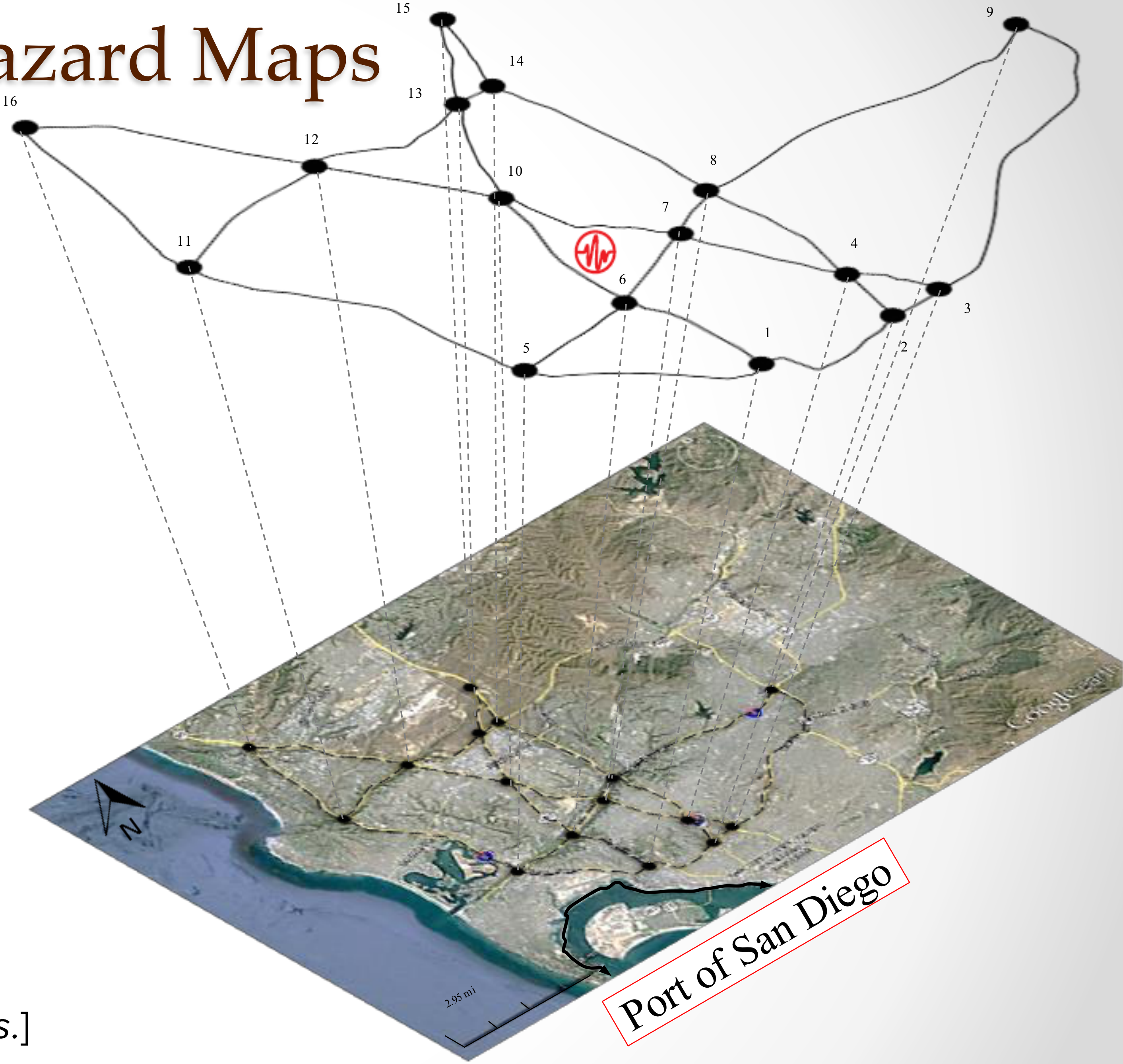
Only provide information about each individual location. For **regional analyses**, we need to have **correlated sets of data**.



Source: USGS

Hazard Scenarios –Vs – Hazard Maps





[Karamlou and Bocchini (2016). *Engineering Structures*.]

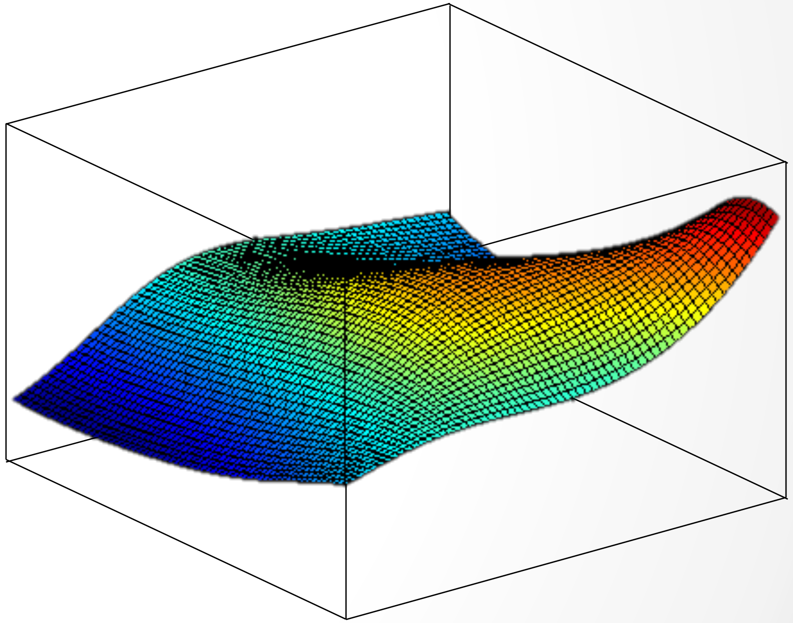
Hazard-Consistent Scenario Selection

Select a suite of scenario events that, in an ensemble sense, matches the probability of exceedance at a grid of locations.

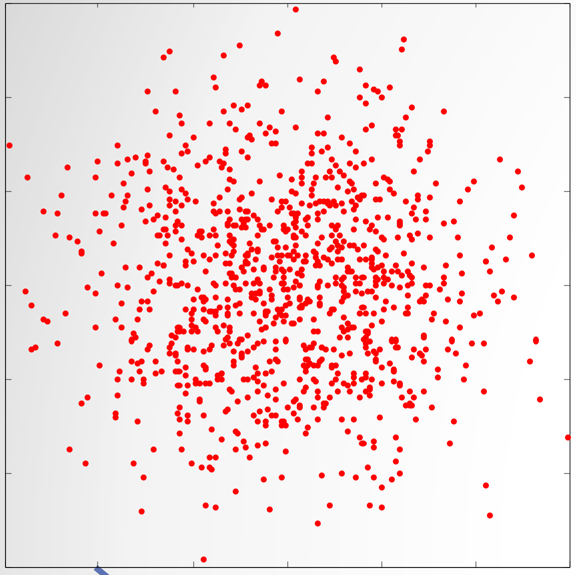
- Matching of the marginal distribution (i.e., hazard curve) is imposed
- Correlation is provided (*hopefully*) by the fact that scenarios are real or realistic

- Is the correlation really matched?
- If yes, are we satisfied with matching the correlation as a by-product?

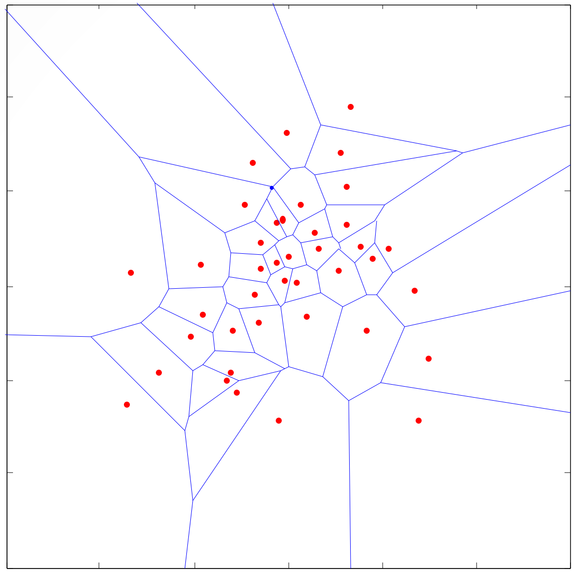
Observation:
The IM is a 2D random field, non-Gaussian and non-homogeneous.



Hazard Quantization: The Idea

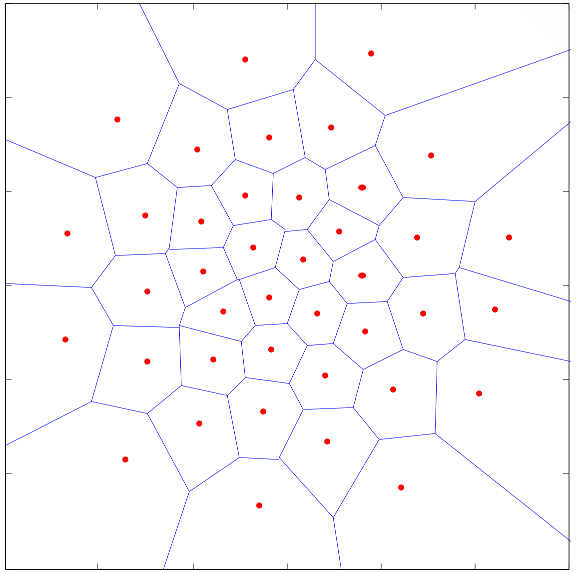


Sample space of all possible scenarios (e.g. each dot is a specific scenario event)



In many cases we can run only few analyses, because of their computational complexity

so we try to “weight” them to see how representative they are



We also want to find those few cases that will give us the best possible representation of all scenarios.

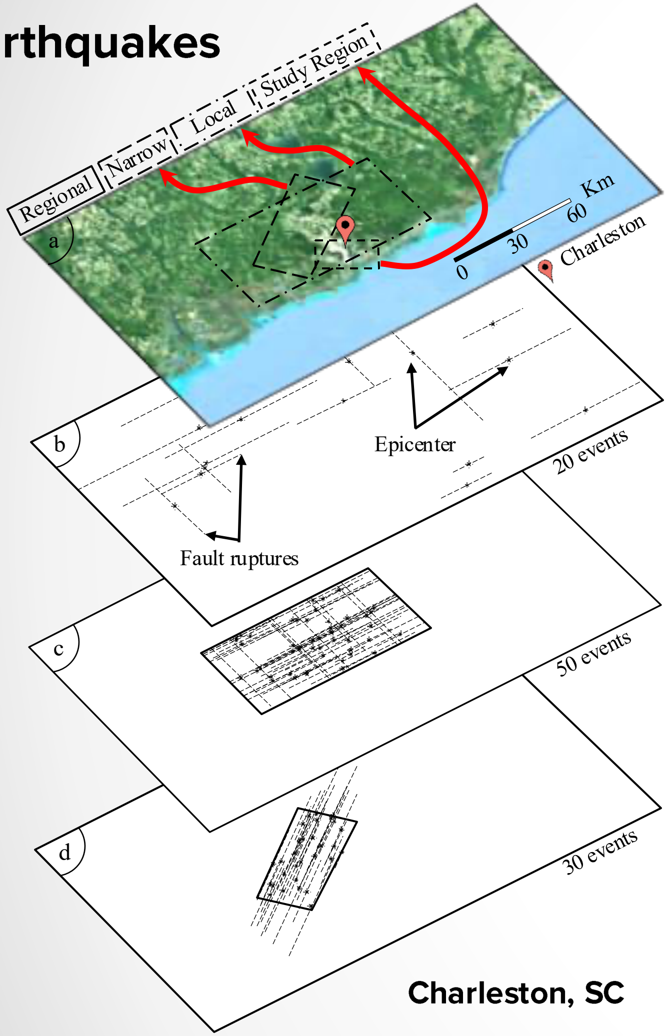
Other approaches:

- k-means clustering (e.g., Stanford U.)
- Optimization-based probabilistic scenario (e.g., U. of Delaware)
- Closed form analysis of correlation (e.g., UIUC)
- …

[Miranda and Bocchini (2015). *Applied Mathematics and Computation.*]
[Christou et al. (2016). *Probabilistic Engineering Mechanics.*]

Hazard Quantization: Example Applications

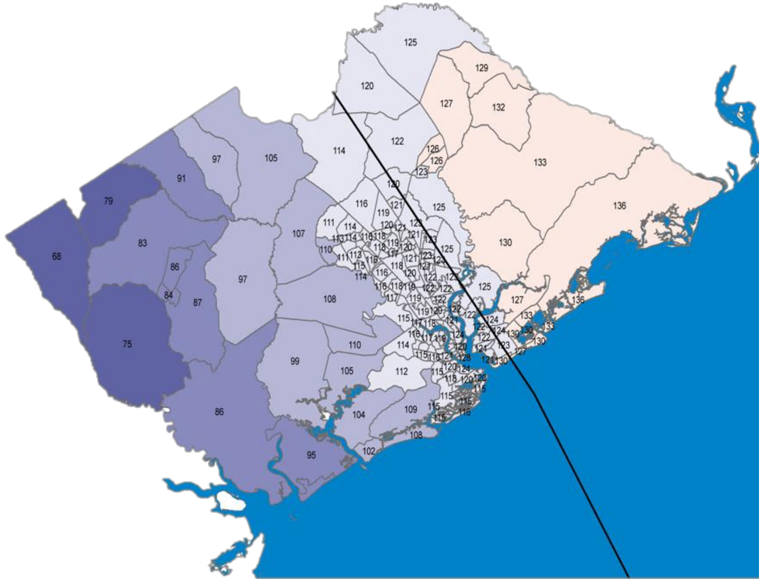
Earthquakes



Charleston, SC

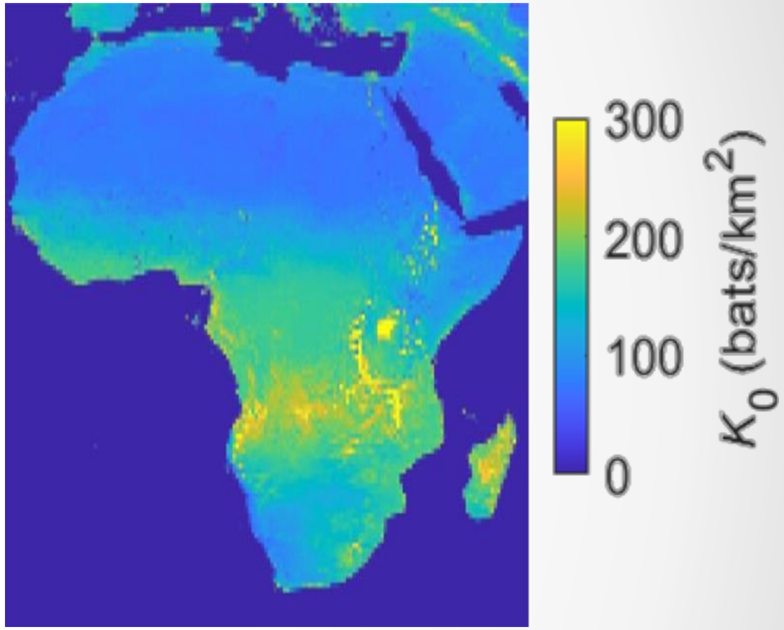
[Christou et al. (2017). *Journal of Risk and Uncertainty in Engineering Systems.*]

Hurricanes



[Ma et al. (2022). *Reliability Engineering and System Safety.*]

Ecological hazards

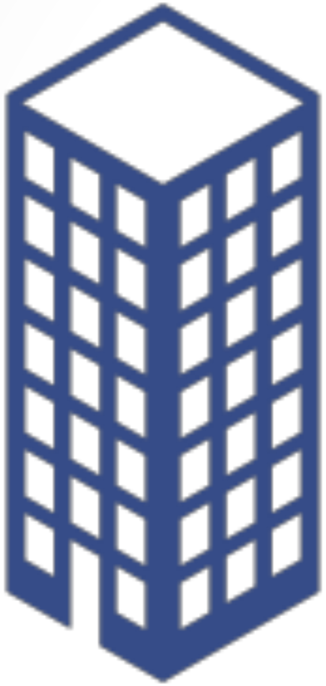


[Mursel et al. (2023). *Ecology and Evolution.*]

- Other applications to stochastic mechanics, life-cycle functions, ground motion time histories, and more.
- Hybrid Quantization (to include historical records)
- Multi-step Hazard Quantization (to have differential accuracy)

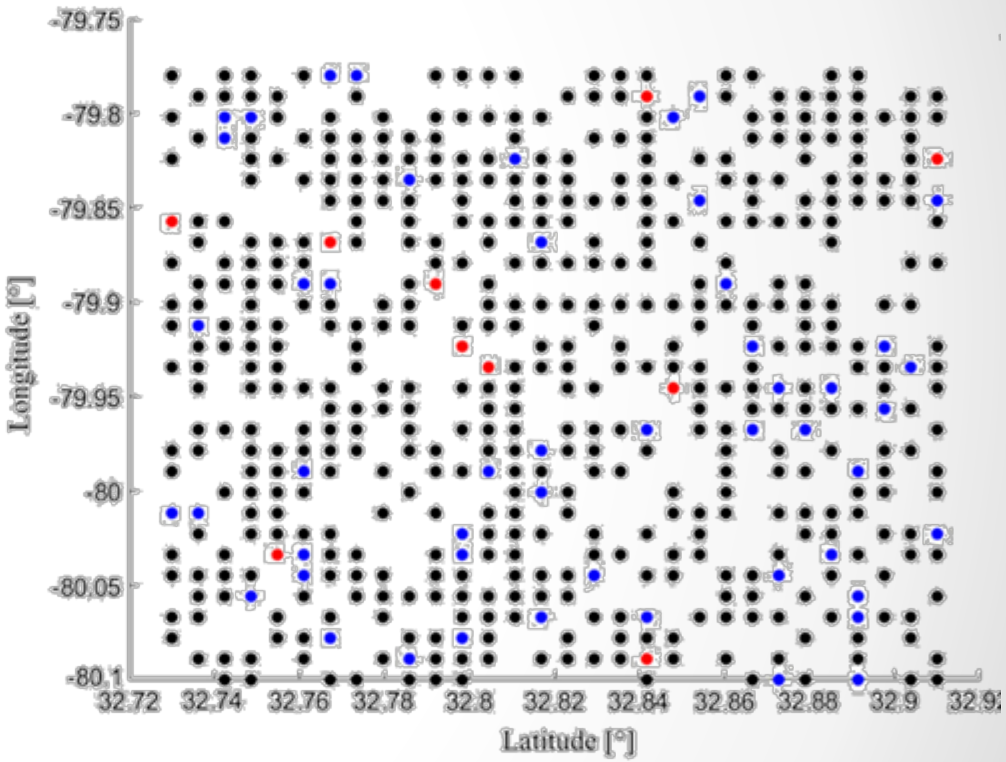
Hazard Quantization: Application to Building Portfolio

wood light frame for
a single-family dwelling
$S_{a\ (T=0.2\ s)}$



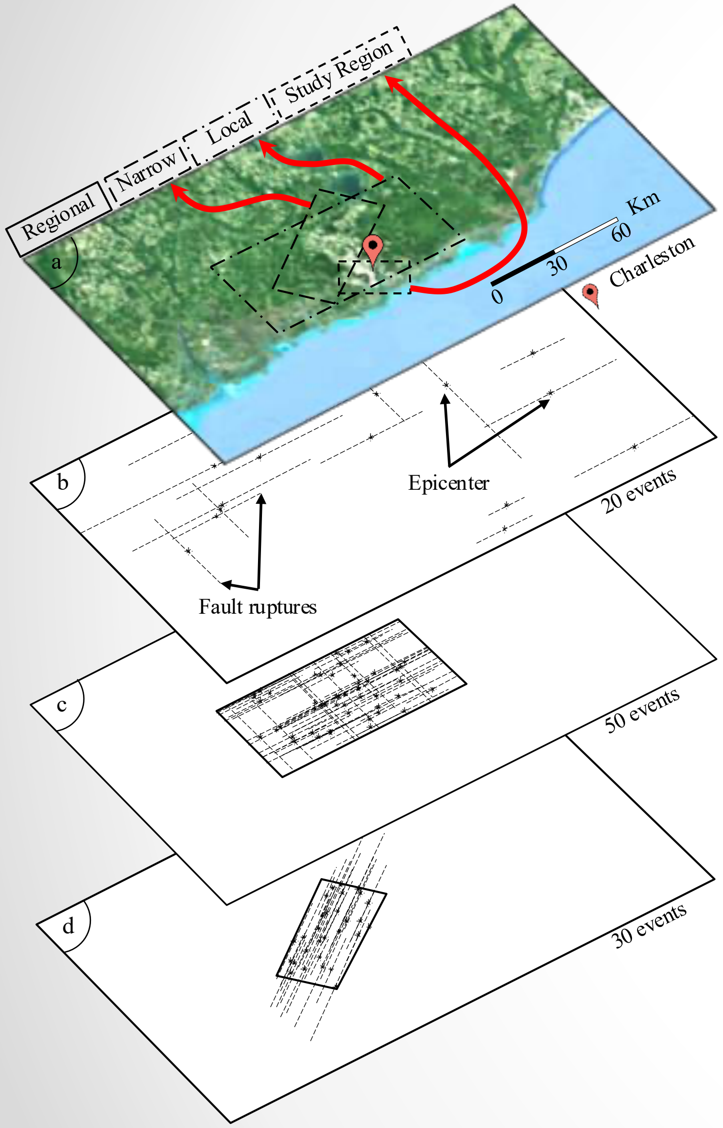
multi-story concrete moment
frame for business services
$S_{a\ (T=1\ s)}$

brick masonry building
$S_{a\ (T=0.2\ s)}$ and $S_{a\ (T=1\ s)}$



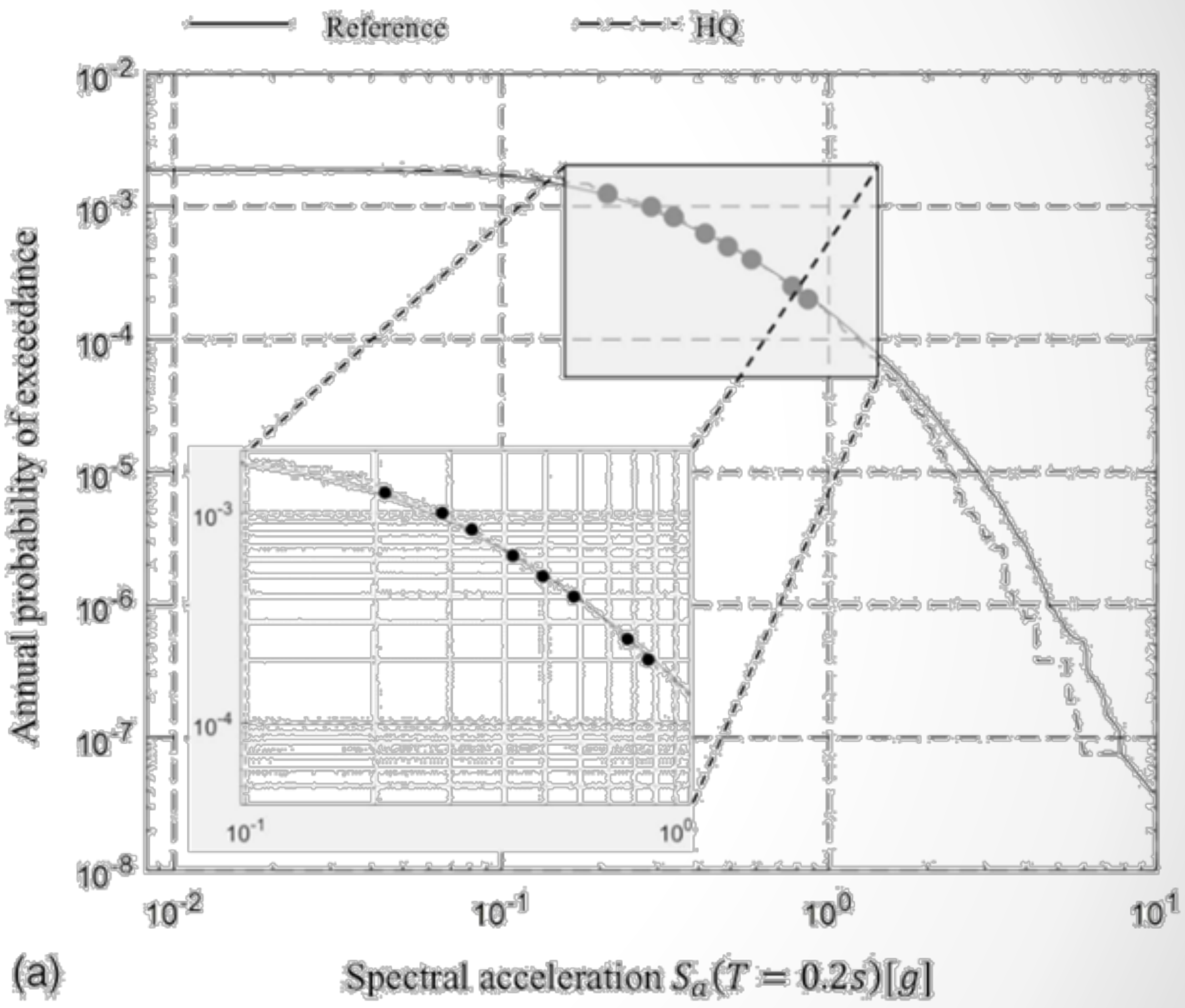
[Ma et al. (2022). *Journal of Risk and Uncertainty in Engineering Systems.*]

Hazard Model: Scenario Selection by Hazard Quantization



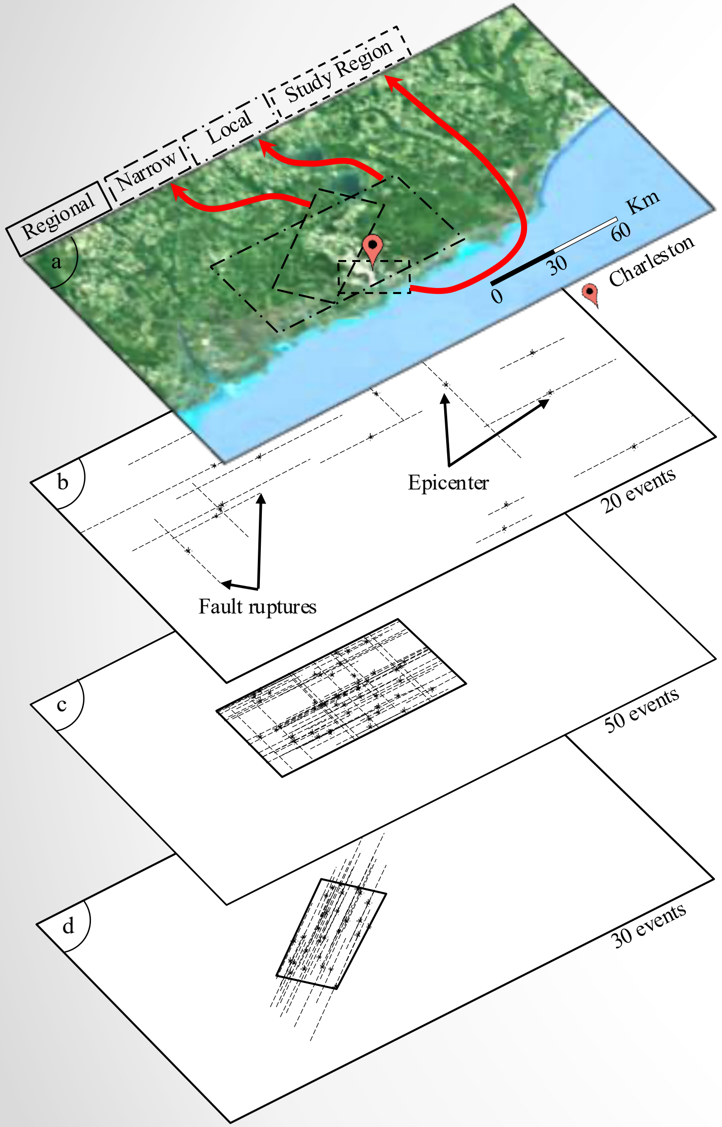
50,000 Scenario events

500 Scenario events



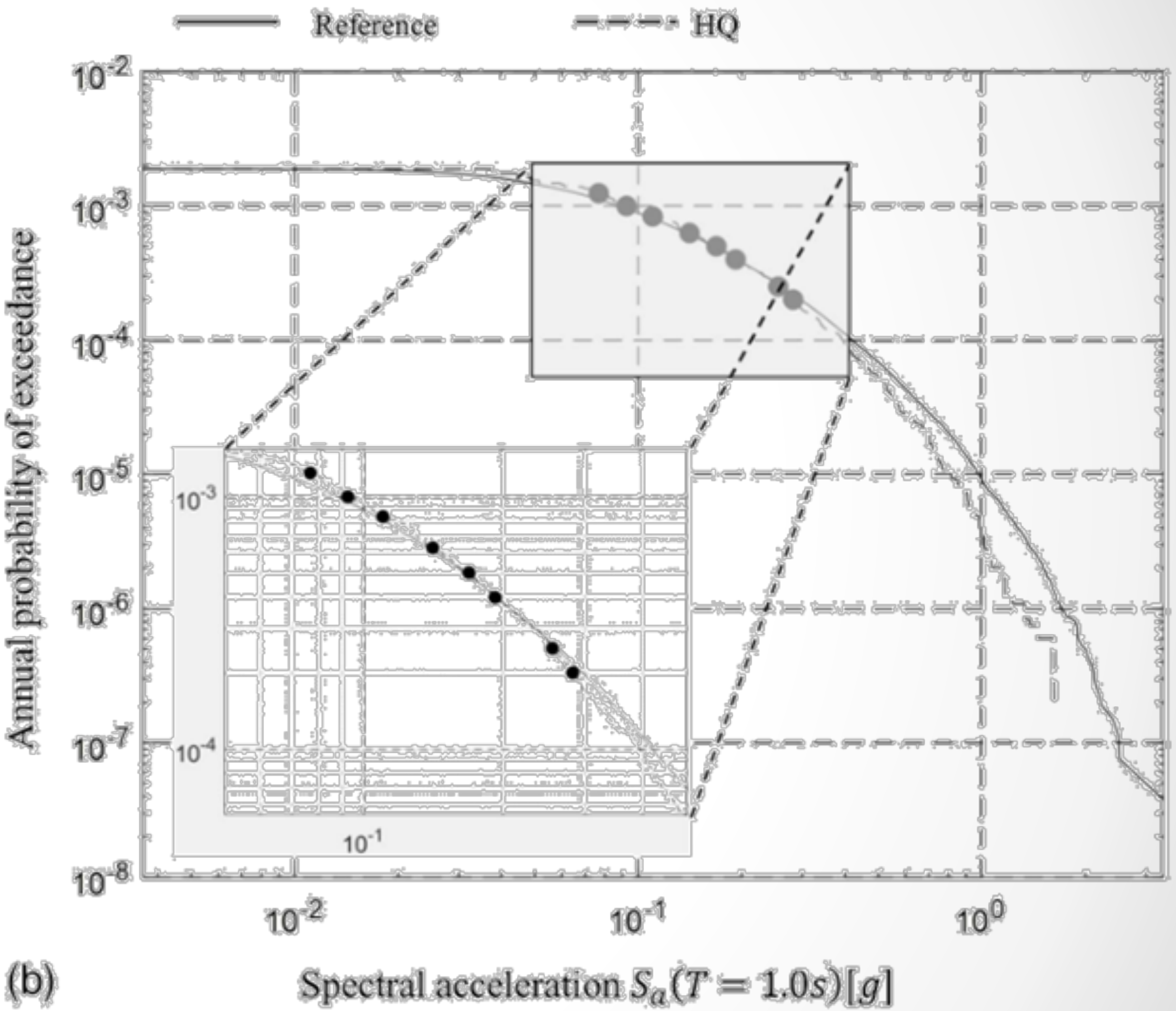
[Christou et al. (2017). *Journal of Risk and Uncertainty in Engineering Systems.*] [Ma et al. (2022). *Journal of Risk and Uncertainty in Engineering Systems.*]

Hazard Model: Scenario Selection by Hazard Quantization



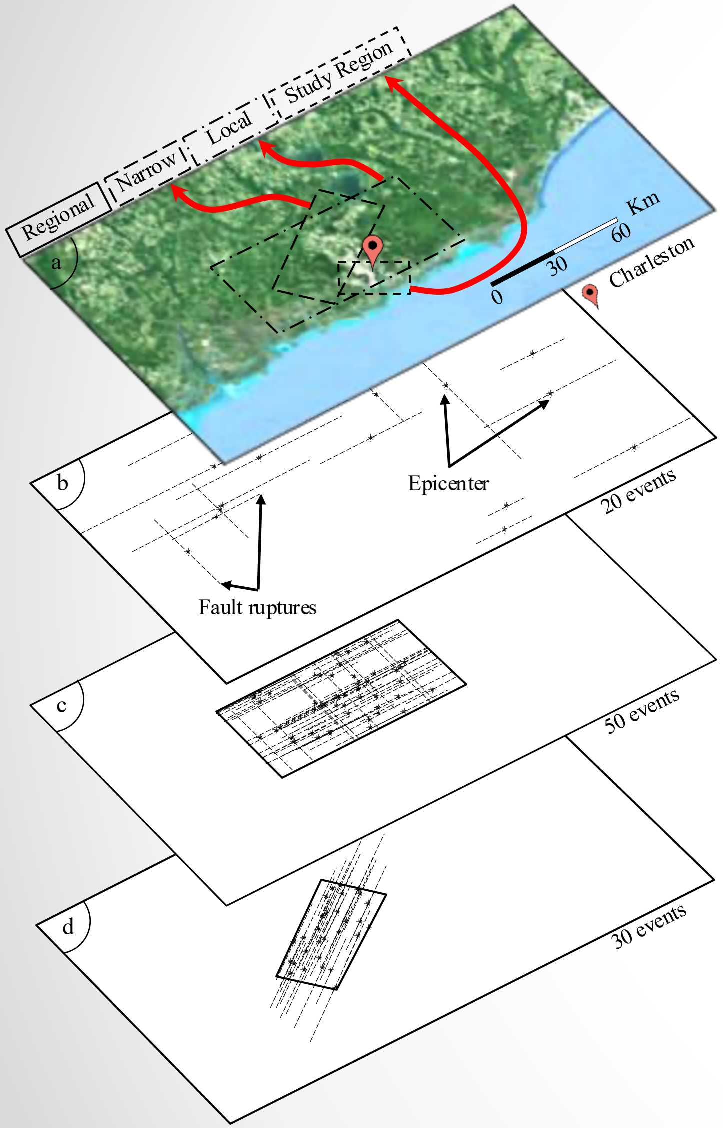
50,000 Scenario events

500 Scenario events



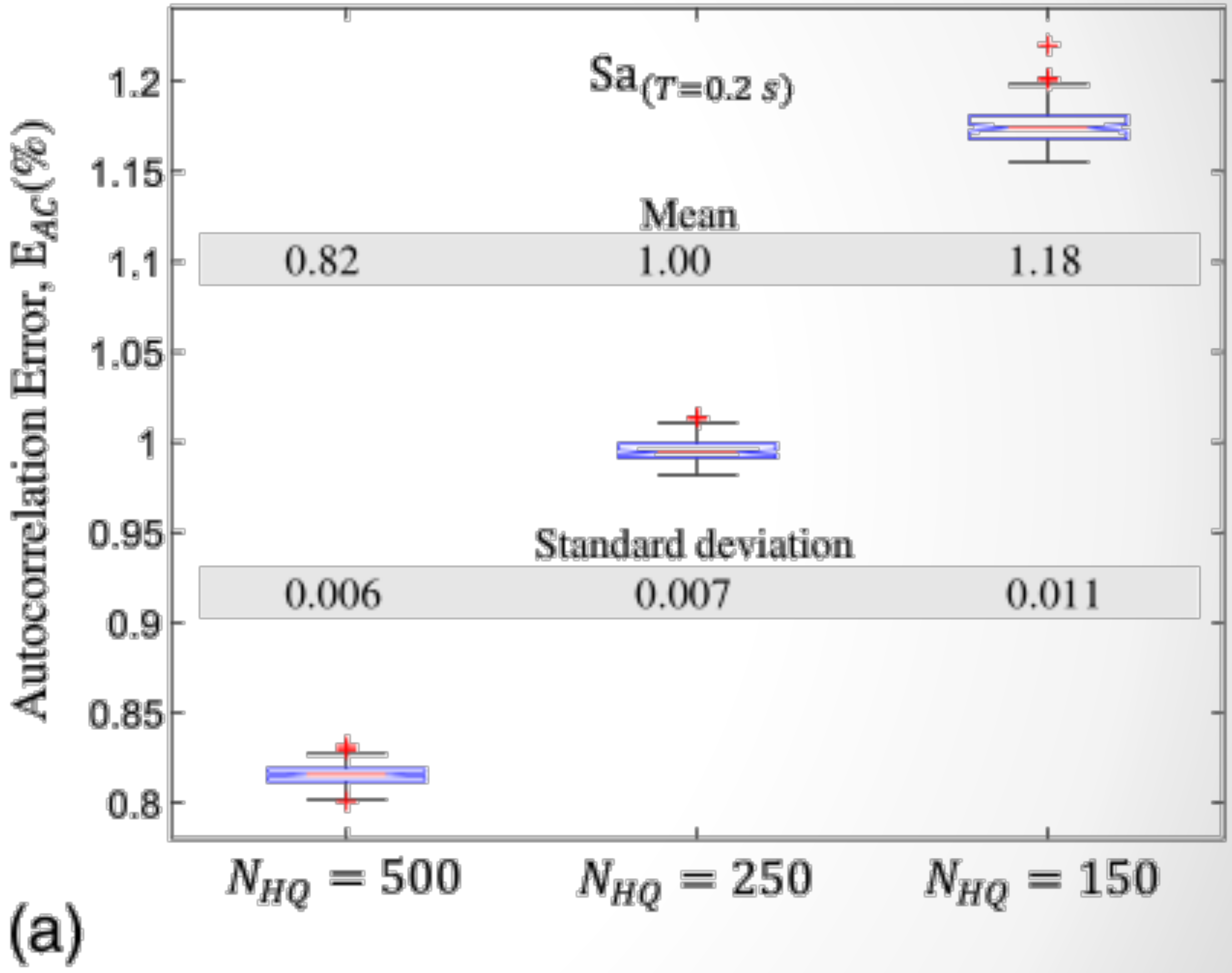
[Christou et al. (2017). *Journal of Risk and Uncertainty in Engineering Systems.*] [Ma et al. (2022). *Journal of Risk and Uncertainty in Engineering Systems.*]

Hazard Model: Scenario Selection by Hazard Quantization



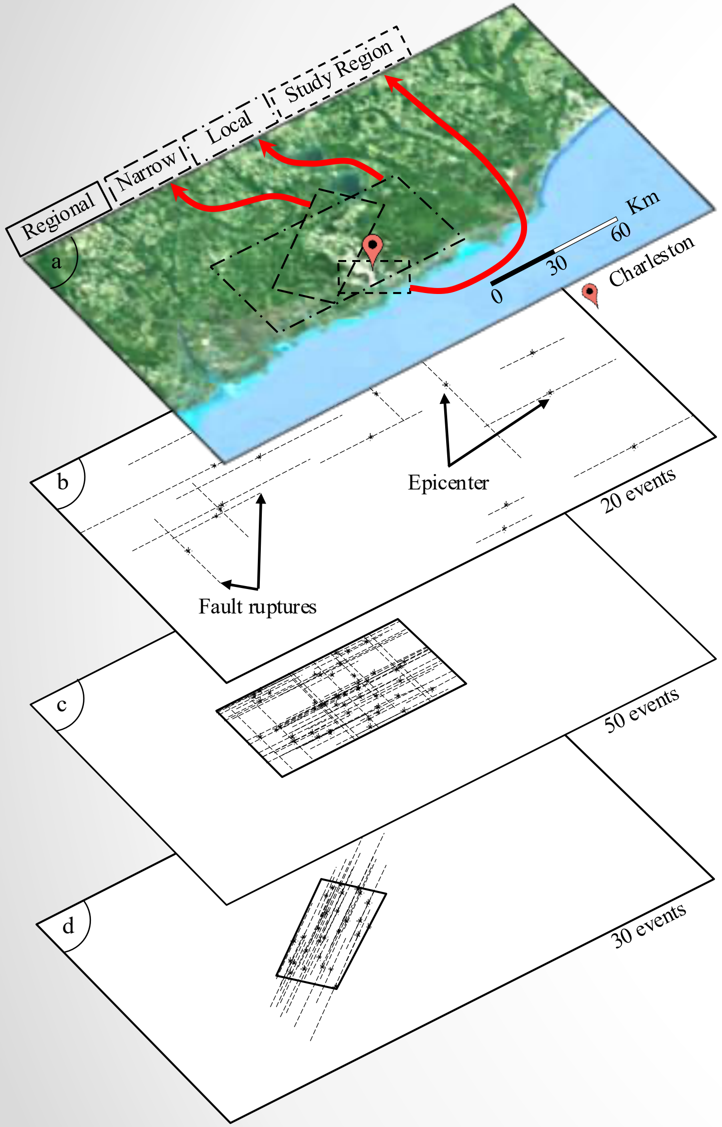
50,000 Scenario events

500 Scenario events



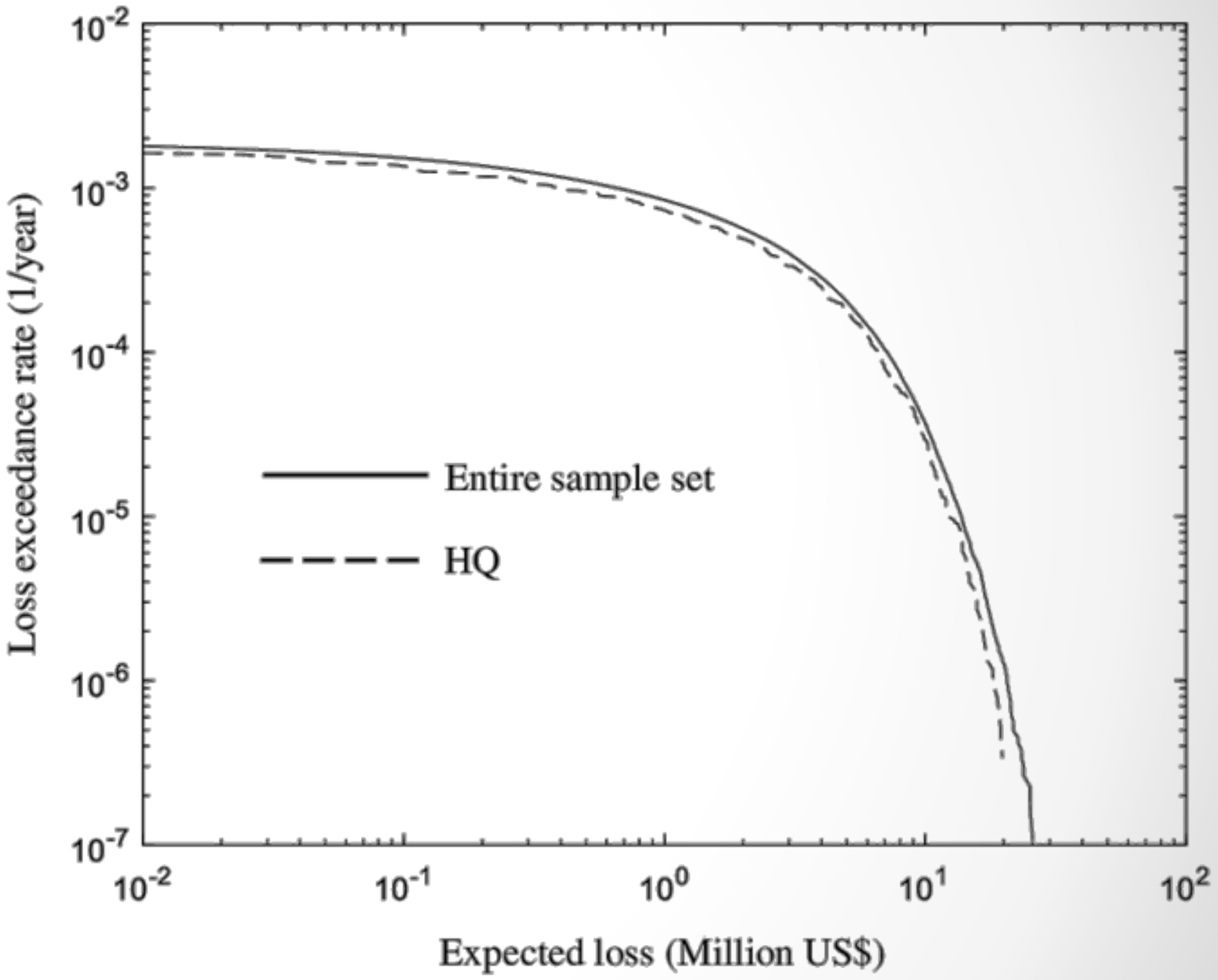
[Christou et al. (2017). *Journal of Risk and Uncertainty in Engineering Systems.*] [Ma et al. (2022). *Journal of Risk and Uncertainty in Engineering Systems.*]

Hazard Model: Scenario Selection by Hazard Quantization



50,000 Scenario events

500 Scenario events

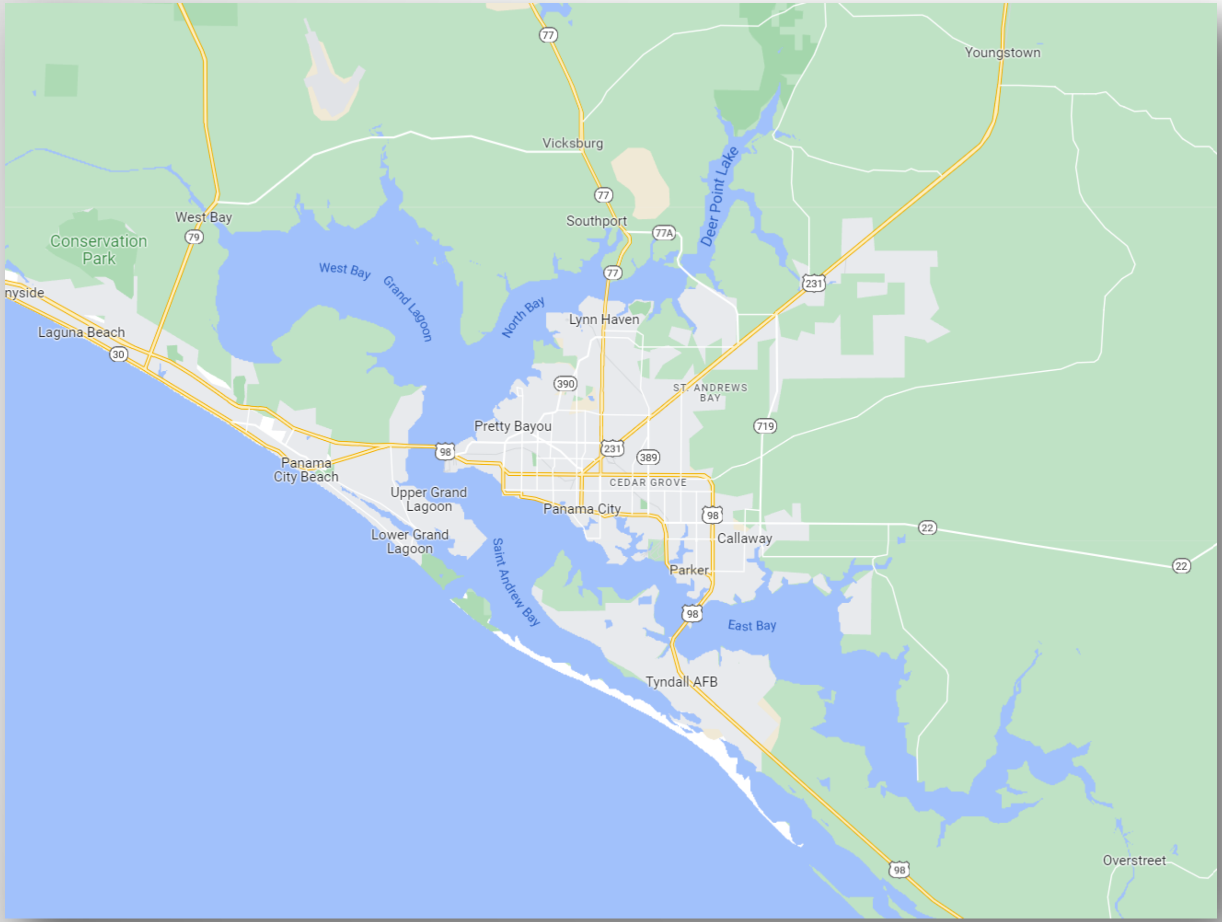


[Christou et al. (2017). *Journal of Risk and Uncertainty in Engineering Systems.*]

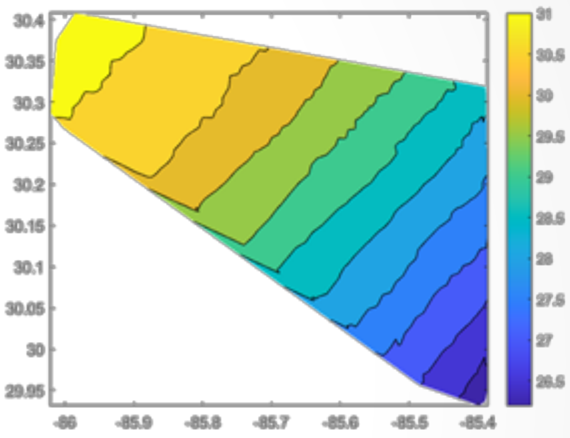
[Ma et al. (2022). *Journal of Risk and Uncertainty in Engineering Systems.*]

Hazard Model: Scenario Selection by Hazard Quantization

Application to joint wind velocity and storm depth

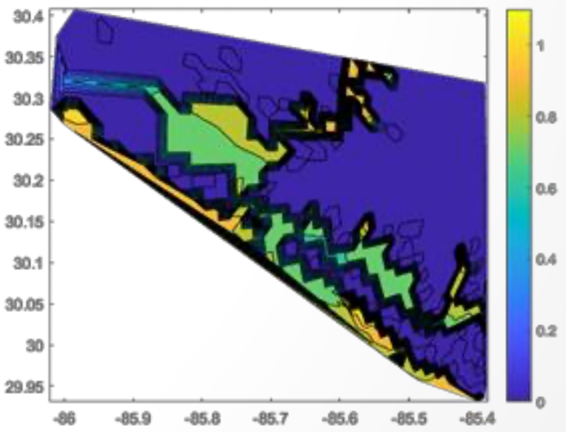


Intensity Measure 1



Wind Speed [m/s]

Intensity Measure 2

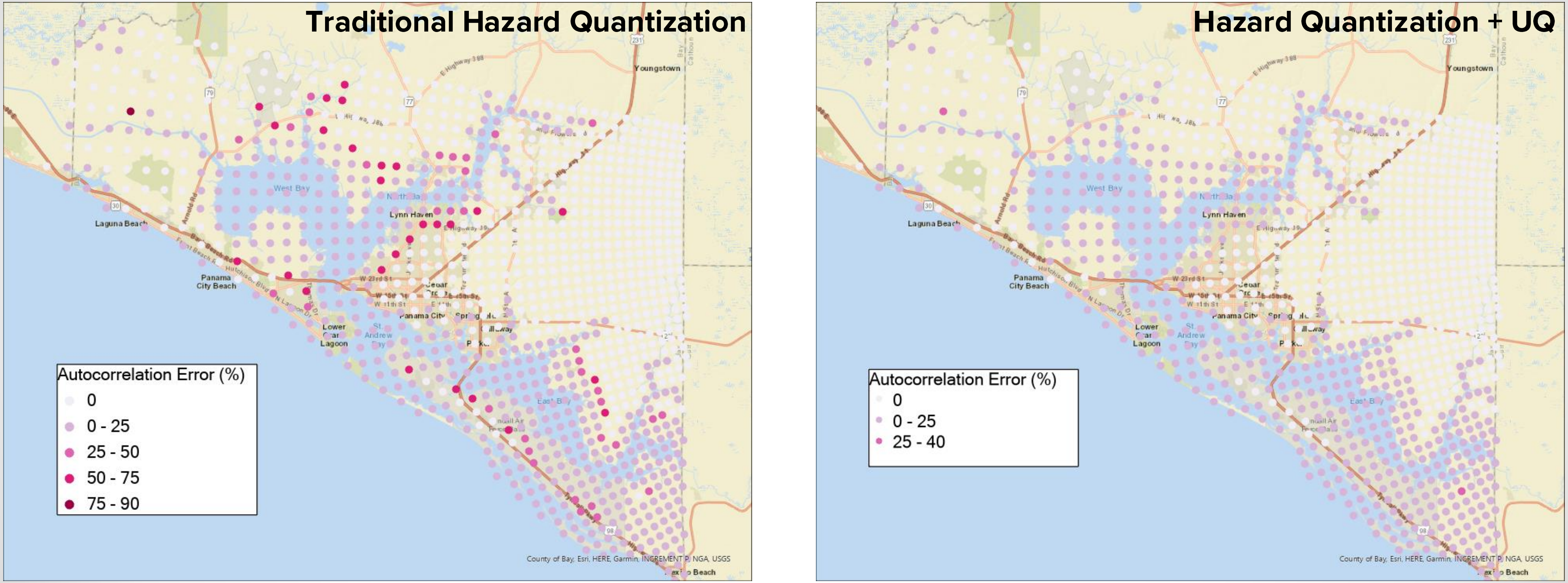


Storm Surge Depth [m]

[Ma et al., *Manuscript in preparation.*]

Hazard Model: Scenario Selection by Hazard Quantization

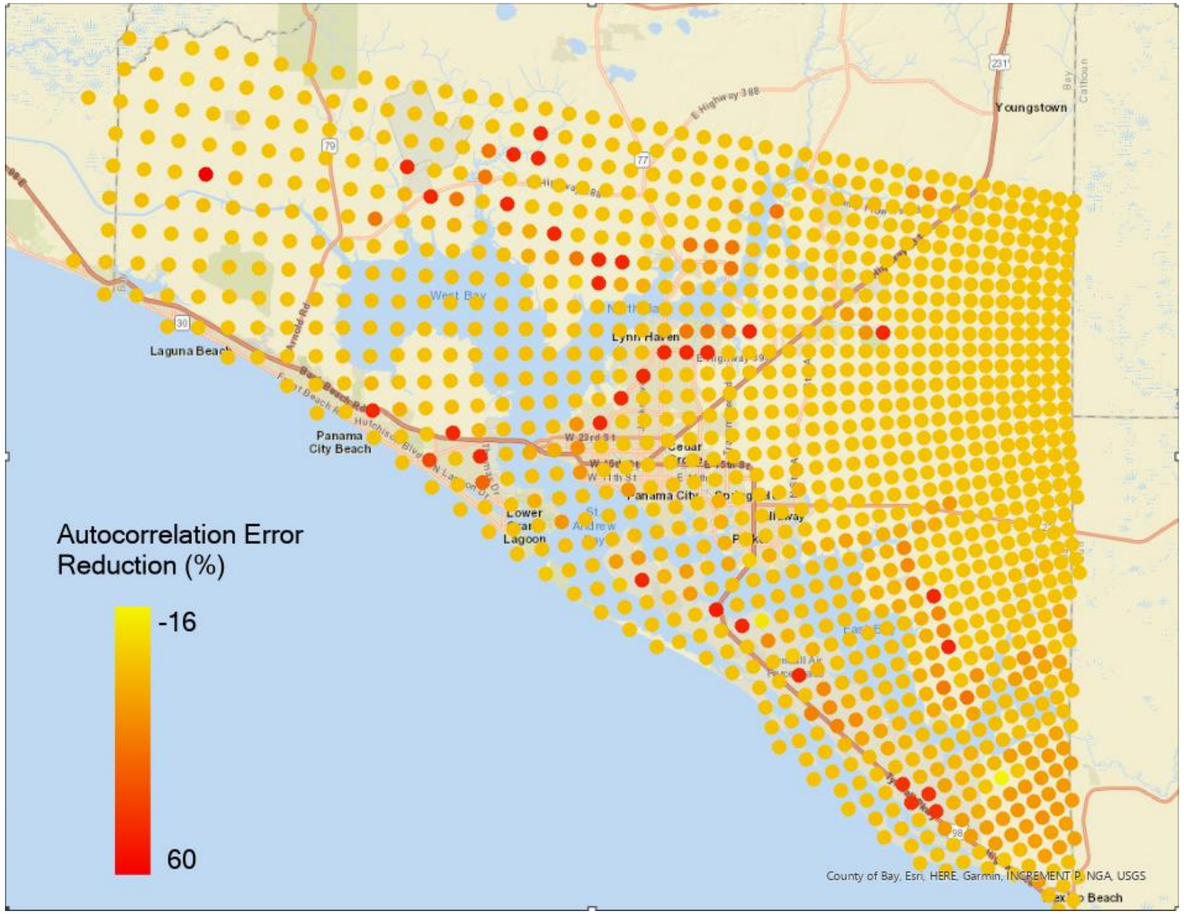
Application to joint wind velocity and storm depth (13,606 → 1,000 scenarios)



[Ma et al., *Manuscript in preparation.*]

Hazard Model: Scenario Selection by Hazard Quantization

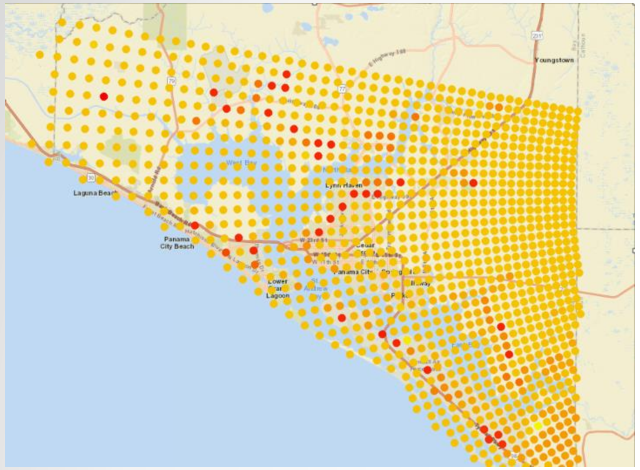
Application to joint wind velocity and storm depth (13,606 → 1,000 scenarios)



Similar results also with only 500 scenarios

[Ma et al., *Manuscript in preparation.*]

Topics of This Webinar

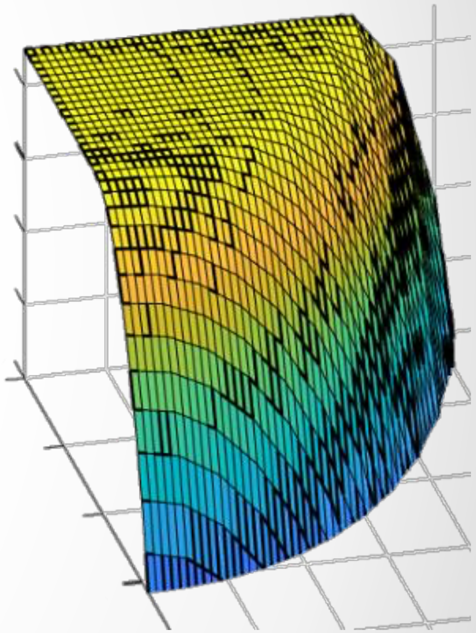


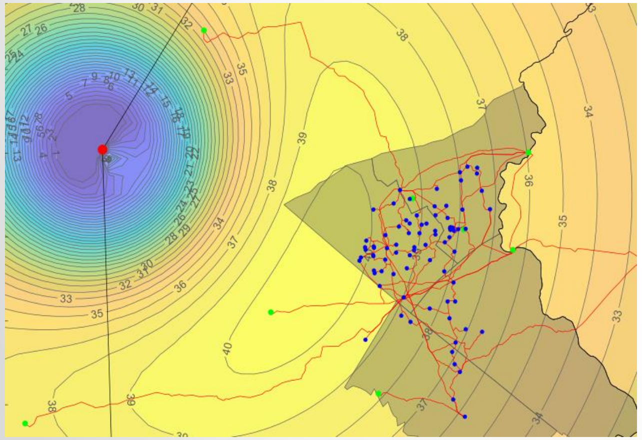
Approximation of the probability space: scenario selection

1

2

Approximation of the structural behavior: fragility models





Approximation of the space and time domain: regional damage and recovery analysis

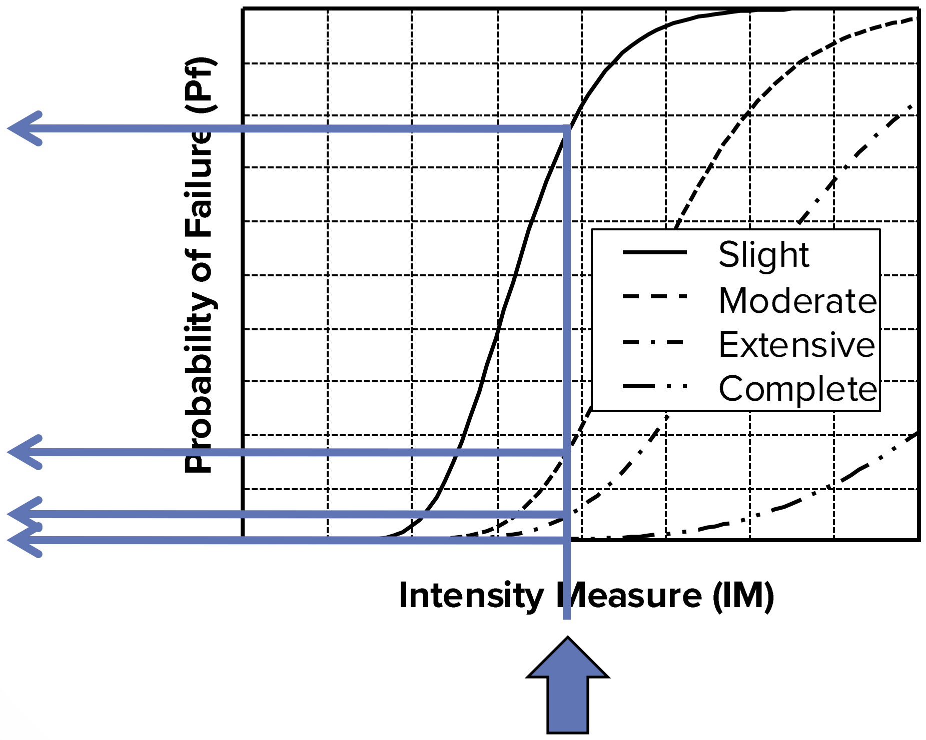
3

Fragility Curves

Conditional probability of reaching or exceeding a damage level given an IM

PROBABILITY
of reaching or exceeding each of the damage levels

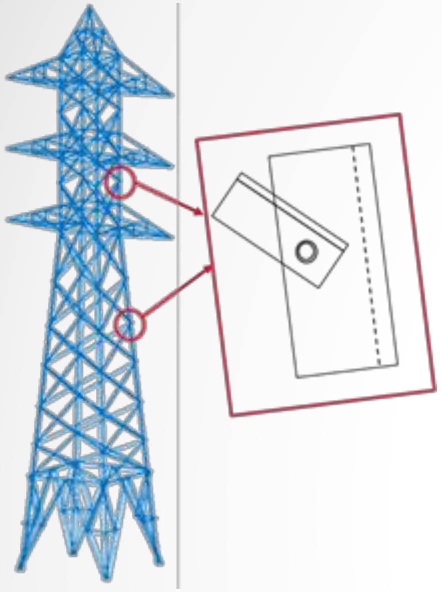
$$Fragility = P[C < D | IM = im]$$



Hazard Scenario

Typically presented with the analytical form of a cumulative distribution function

Bolted Connections



Phases under cycling loading:

- Before slip
- Slippage
- Bearing loading
- Bearing stick
- Bearing slip

+ damage accumulation

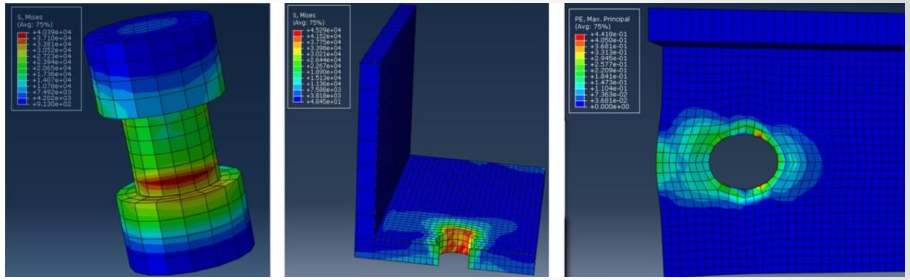
Calibration & Validation

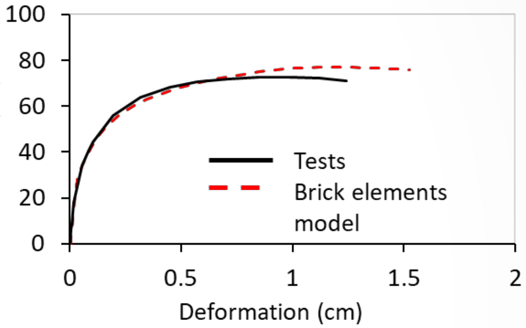
Experimental results

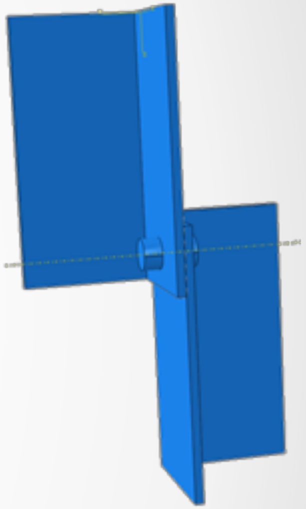
3D FEM model

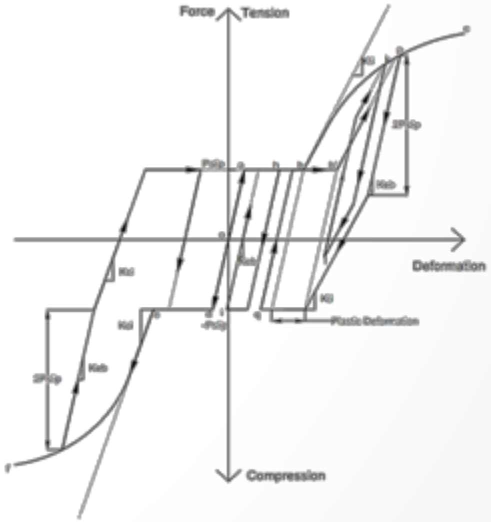
Analytical model

OpenSees element



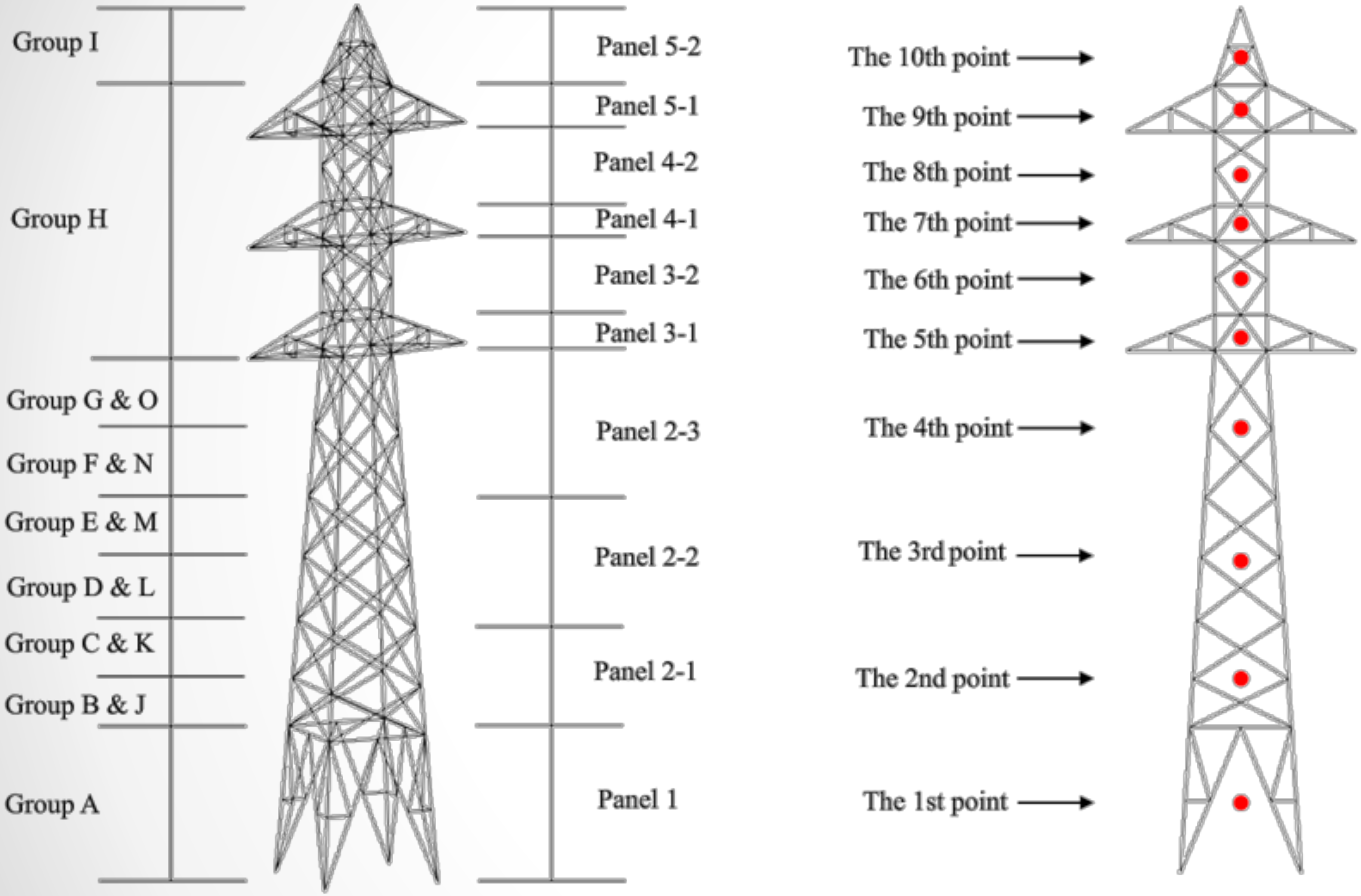






[Ma & Bocchini, *Journal of Engineering Mechanics*, 2019]

Tower Fragility: Wind Loads



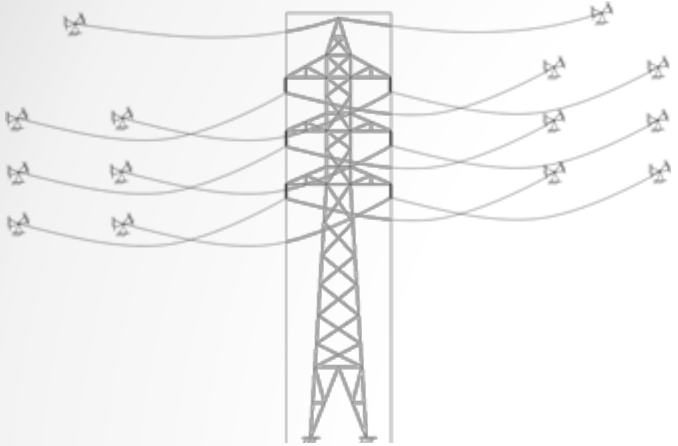
[Ma, Khazaali & Bocchini. *Engineering Structures* (242) 2021.]

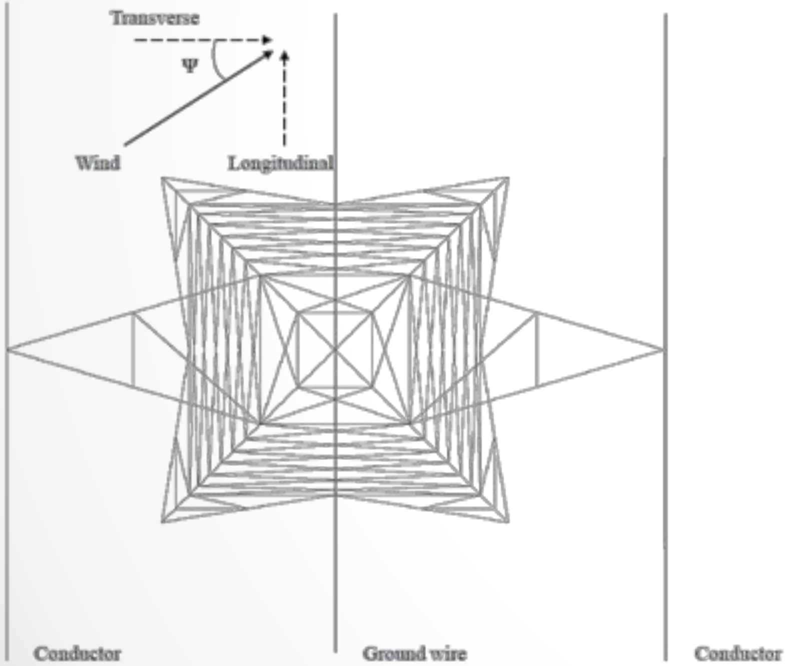
Wind data repository

Comprehensive repository of spatially and temporally correlated wind velocity samples.

[Khazaali, Christou, & Bocchini. *Journal of Structural Engineering*, 2022.]

Tower Fragility: Loads from Conductor Cables





Naive approach

Wind spectrum

SRM (100+ components)

Wind fluctuations

Finite element model

Cable element

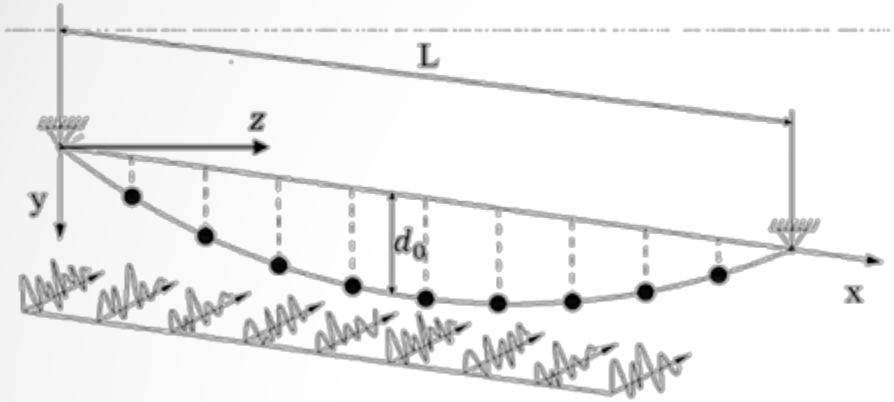
Dynamic analysis

Load on the tower

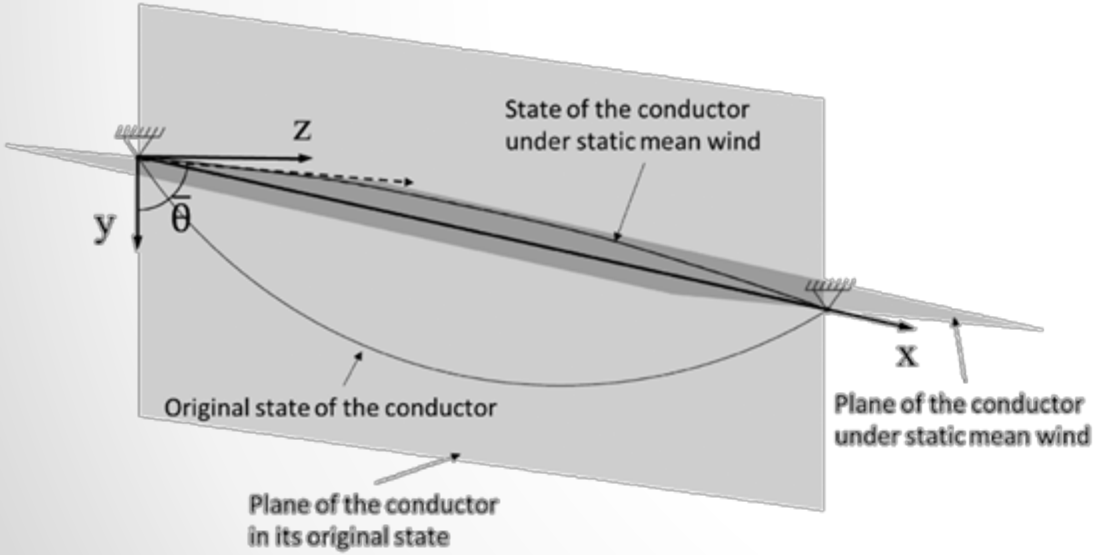
Load transferred by conductor cables?

[Ma, Khazaali & Bocchini. *Engineering Structures* (242) 2021.]

Conductor Cable Dynamics

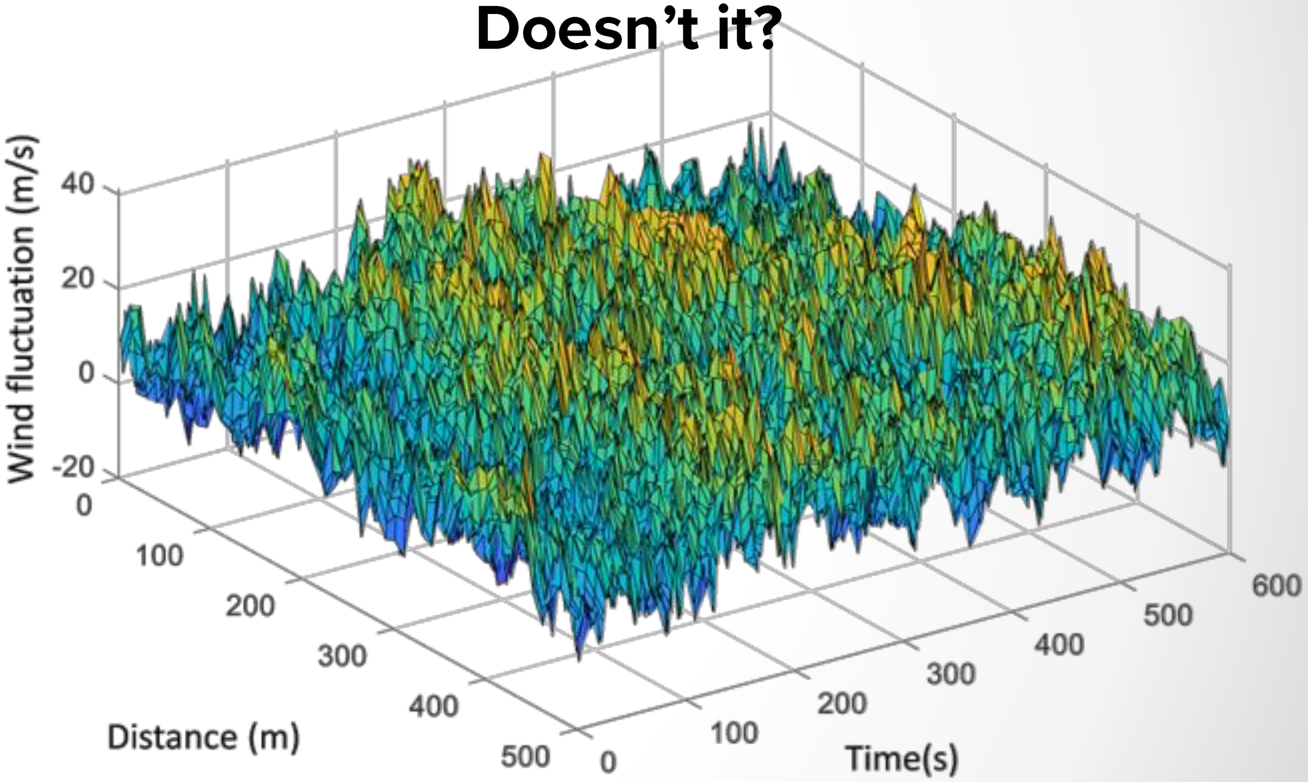


(b)



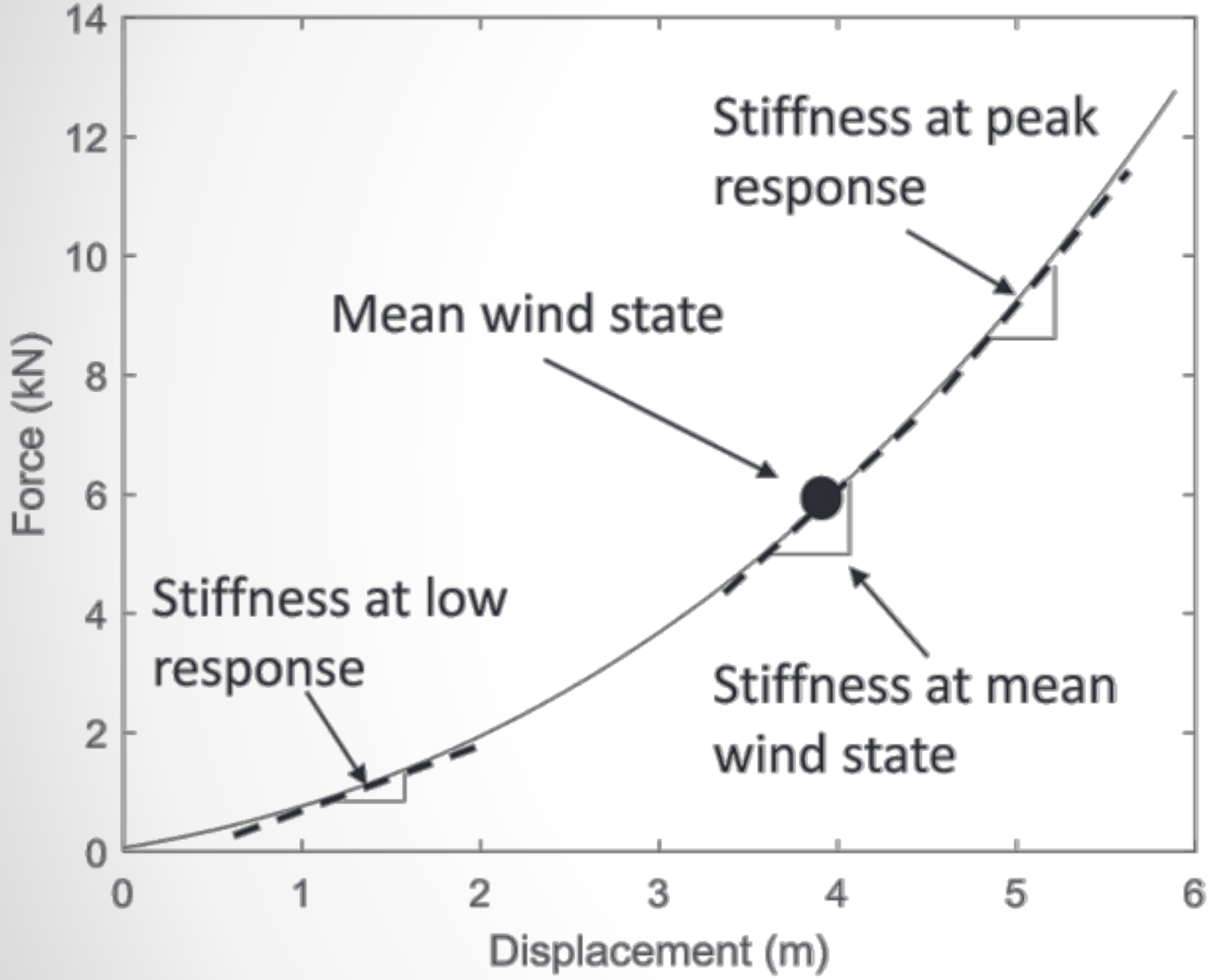
The highly nonlinear behavior of the cables requires nonlinear time-history analysis (repeated ~10^5 millions times)

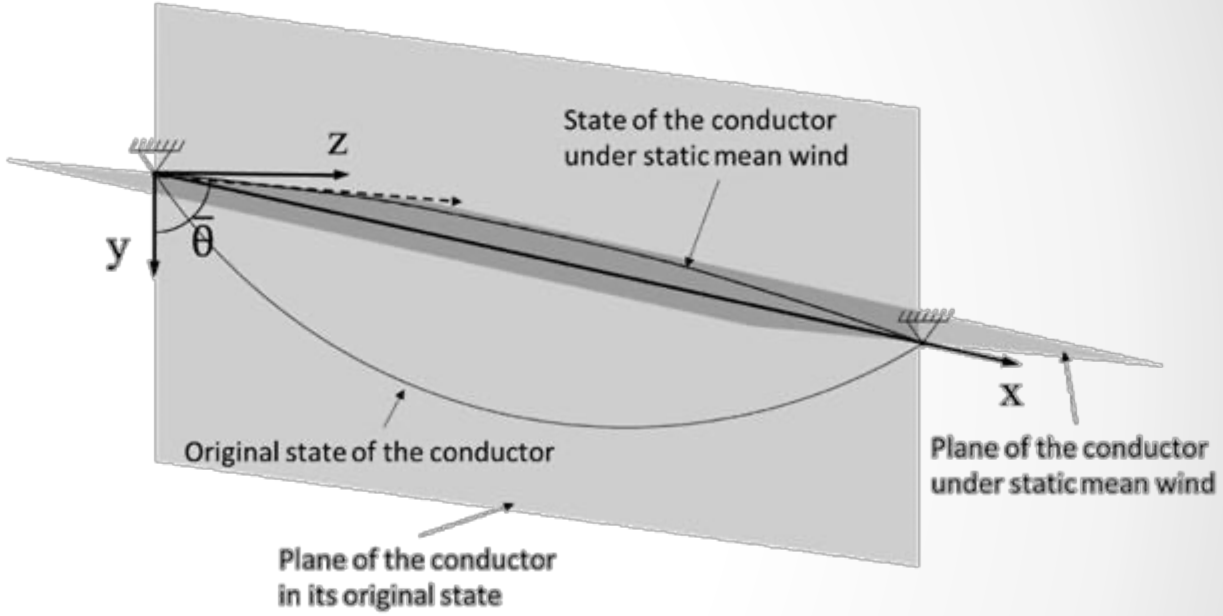
Doesn't it?



[Ma, Bocchini, & Christou. *Structural Safety*, 2020.]

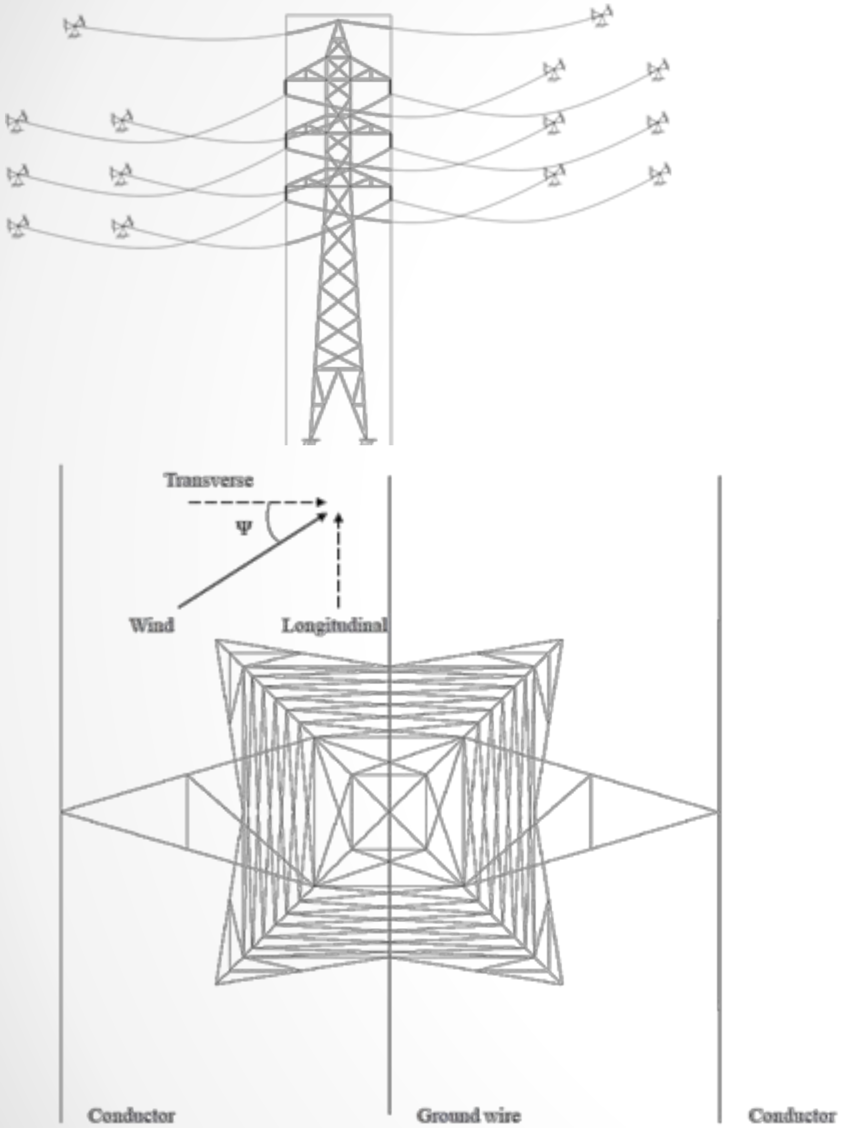
Conductor Cable Dynamics





[Ma, Bocchini, & Christou. *Structural Safety*, 2020.]

Tower Fragility: Loads from Conductor Cables



Naive approach

Wind spectrum

SRM (100+ components)

Wind fluctuations

Finite element model

Cable element

Dynamic analysis

Load on the tower

Proposed Method

Wind spectrum

Modal superposition

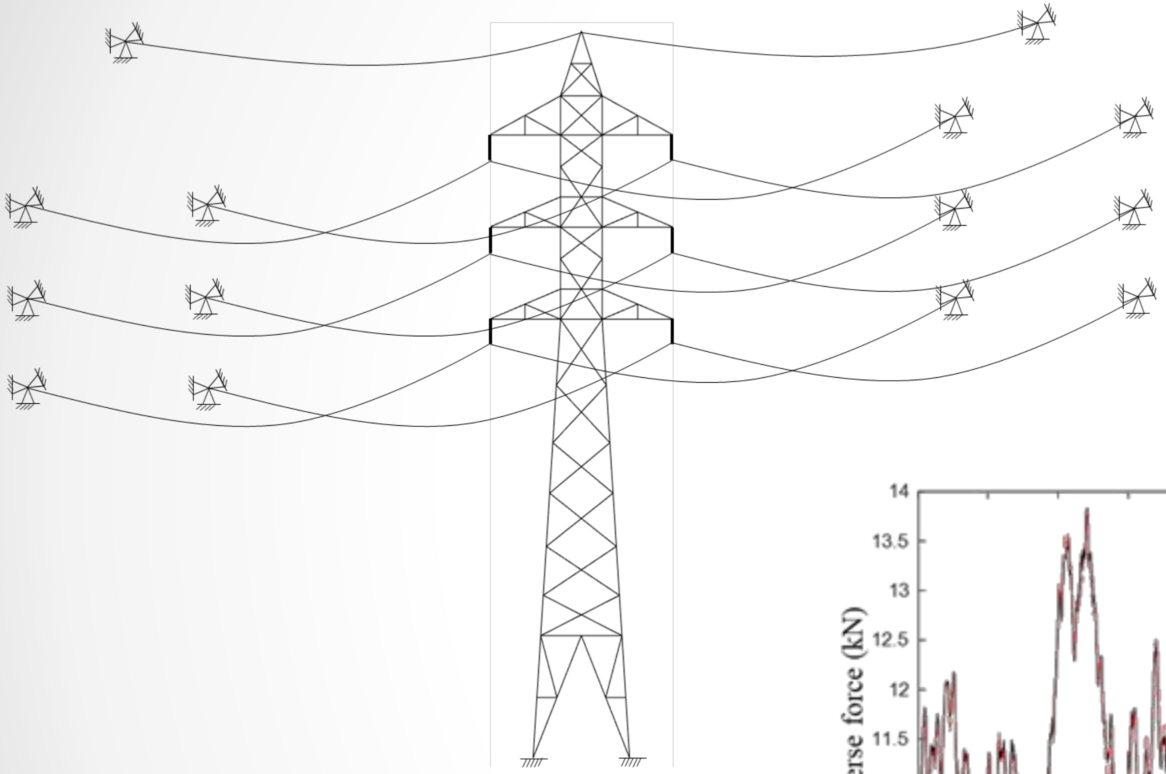
Spectrum of load on tower

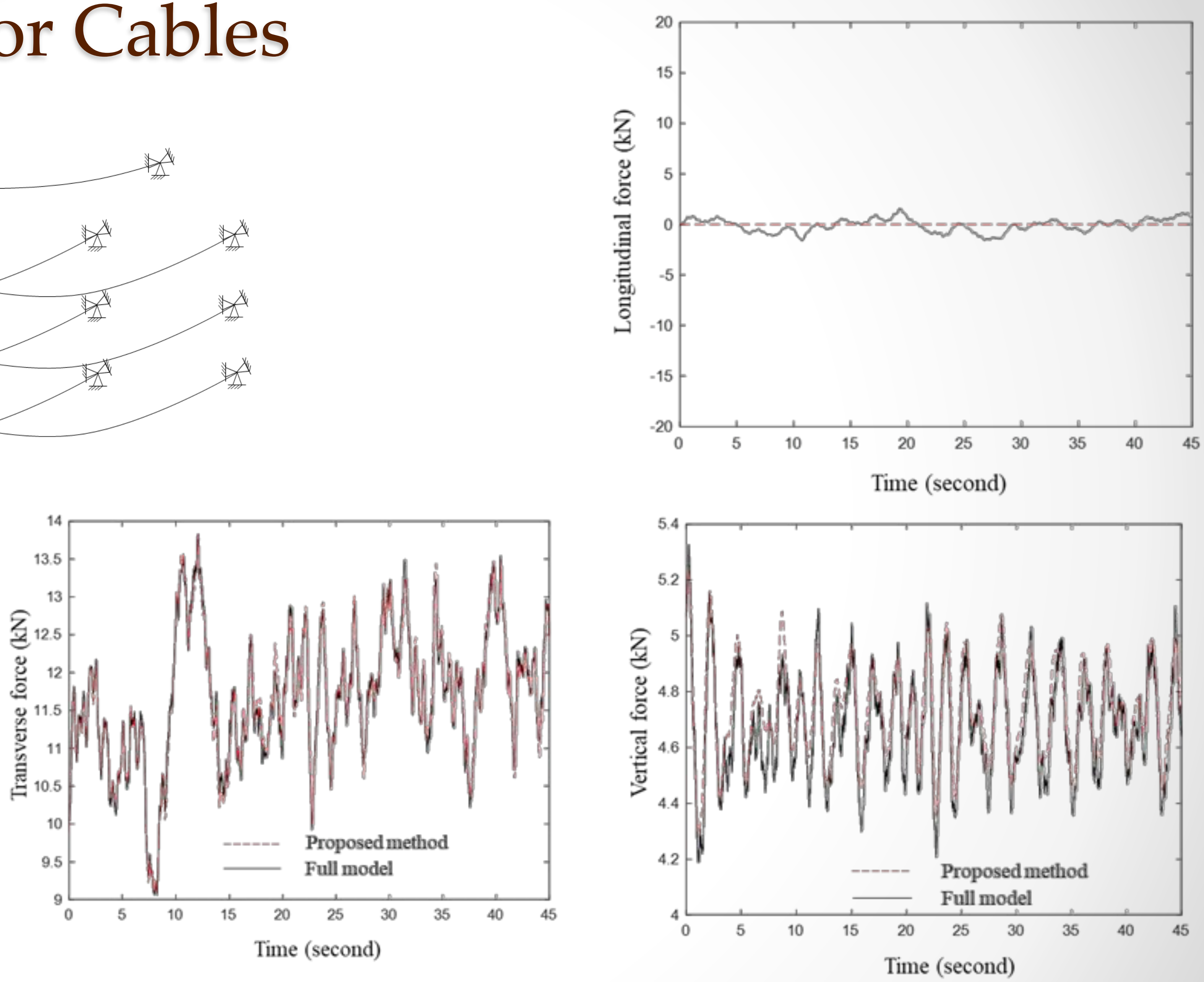
SRM (21 components)

Load on the tower

[Ma, Khazaali & Bocchini. *Engineering Structures* (242) 2021.]

Loads from Conductor Cables

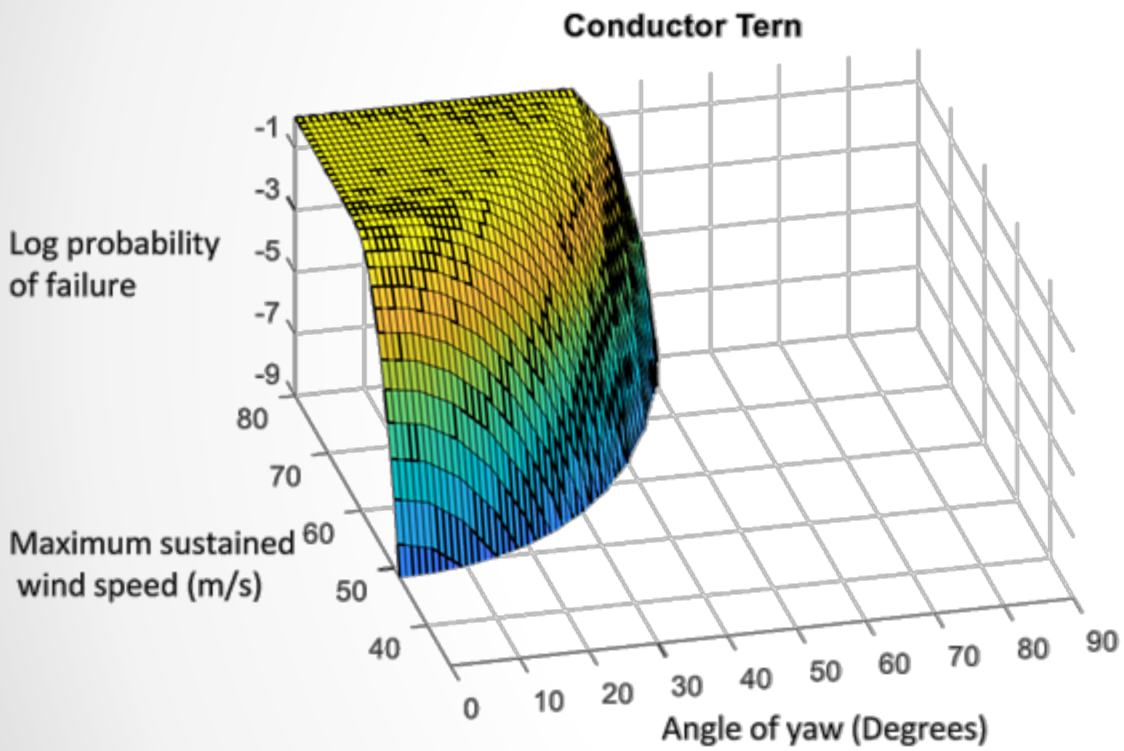


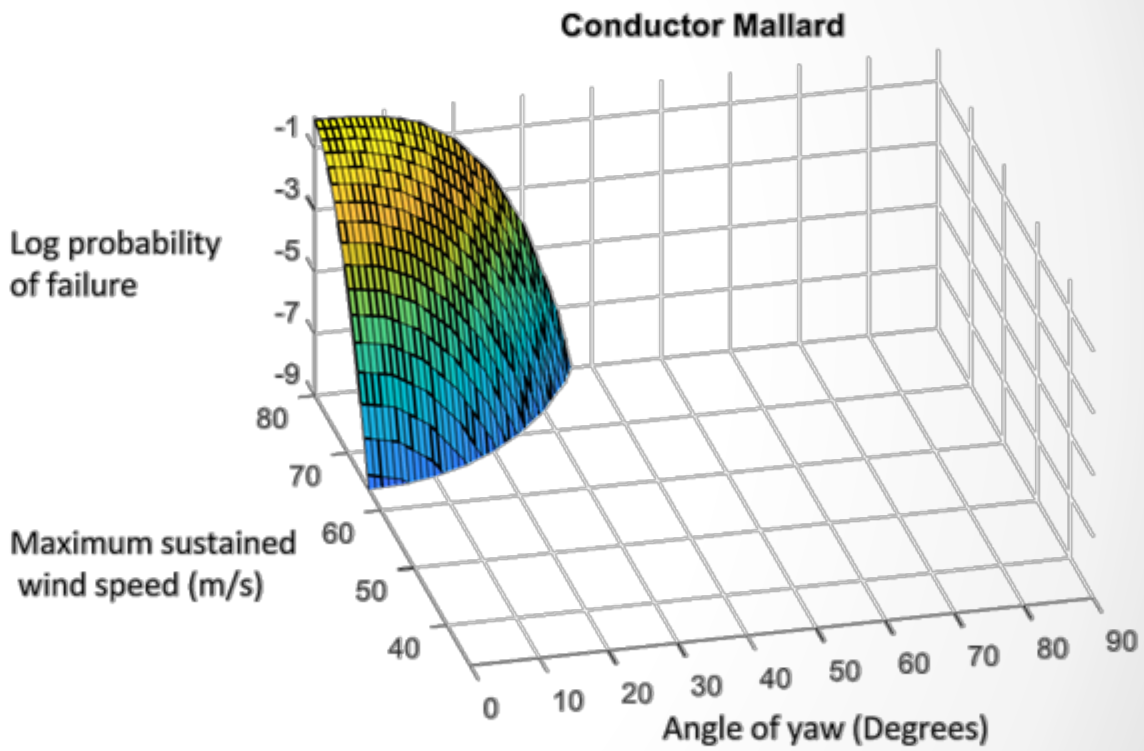


[Ma, Khazaali & Bocchini. *Engineering Structures* (242) 2021.]

Conductor Cable Fragility

Extra benefit: the modal superposition method allows us to compute the spectrum of the response analytically, and to formulate the problem as a first-passage problem, which can be solved in closed form.

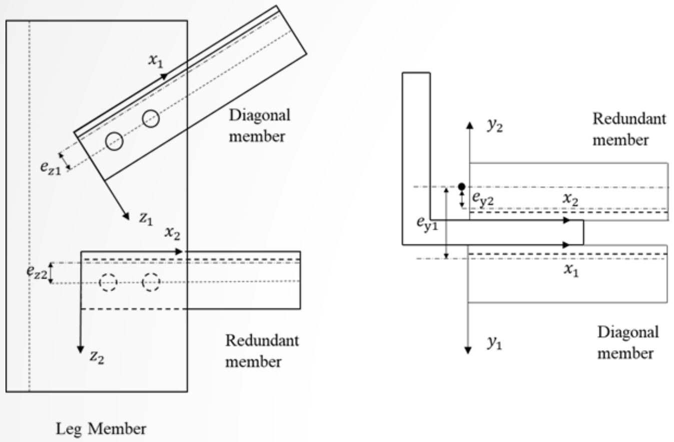




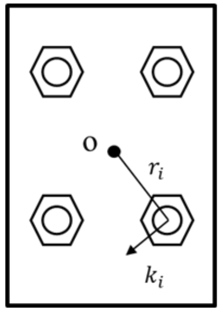
[Ma, Bocchini, & Christou. *Structural Safety*, 2020.]

Tower Fragility: Bolted Connections

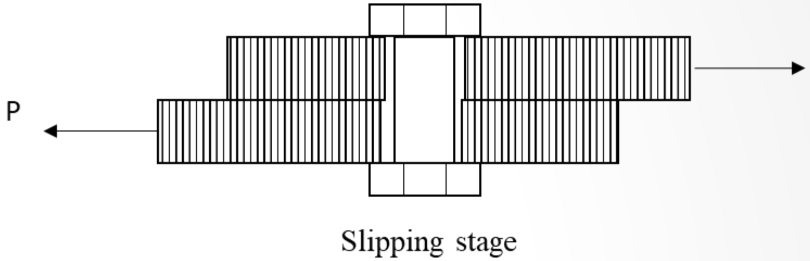
Eccentricity



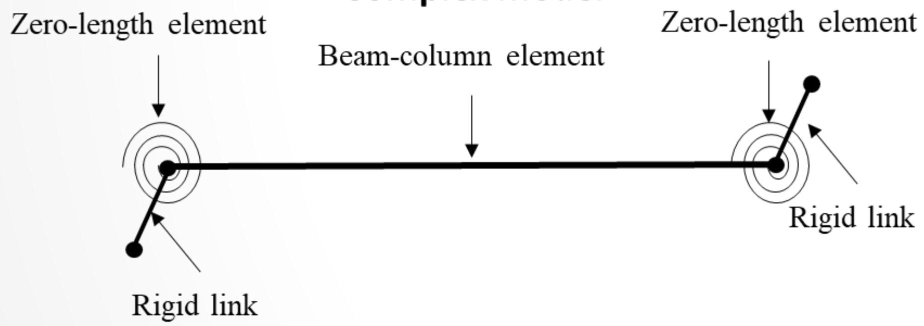
Rotational stiffens



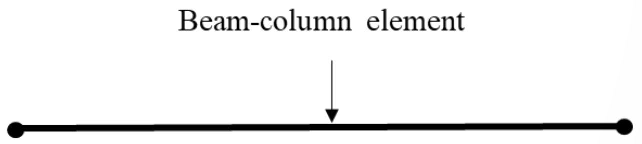
Joint slippage



Complex model



Simple model

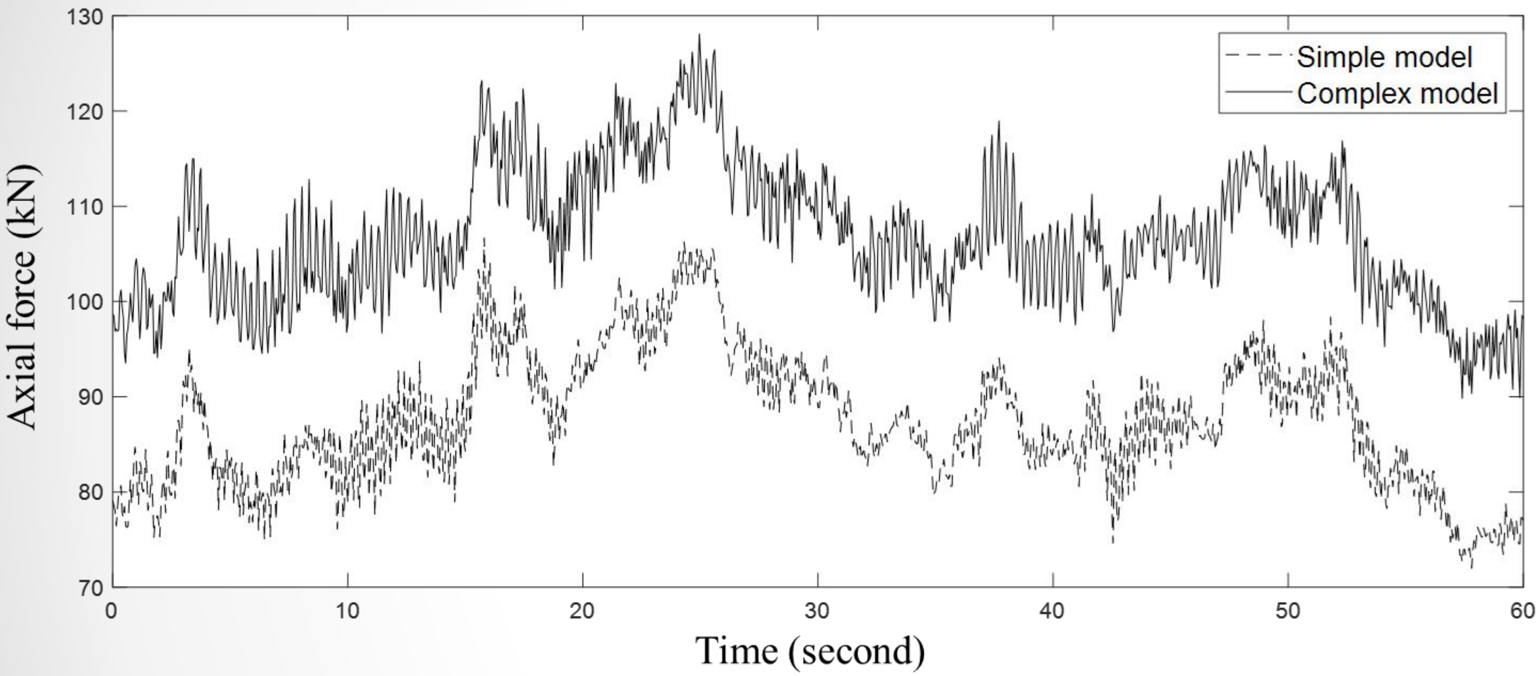


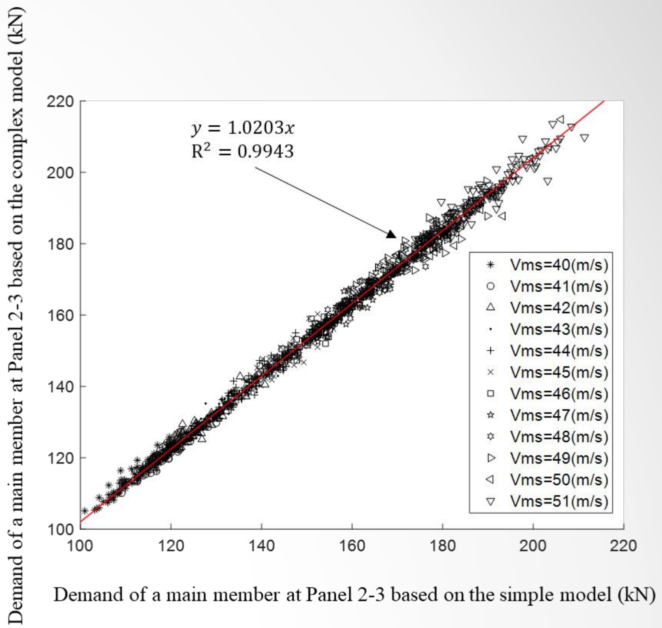
12 hours for a 2-minute dynamic analysis

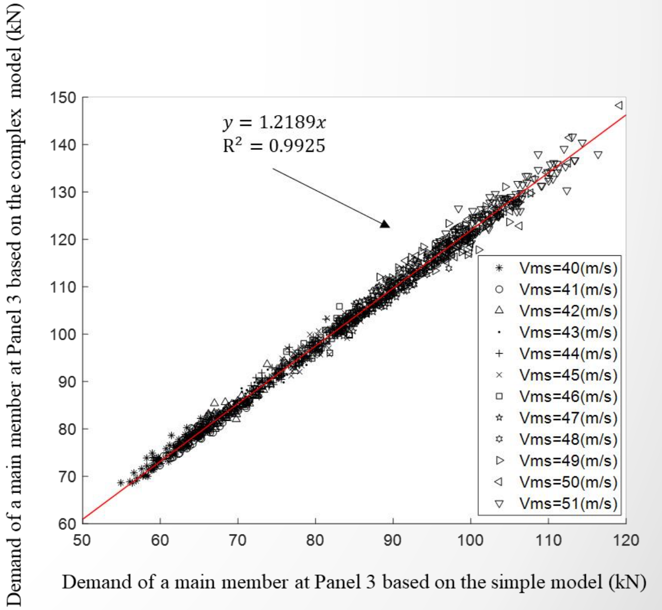
5 minutes for a 2-minute dynamic analysis

[Ma, Khazaali & Bocchini. Component-based fragility analysis of transmission towers subjected to hurricane wind load. *Engineering Structures* (242) 2021.]

Tower Fragility: Bolted Connections

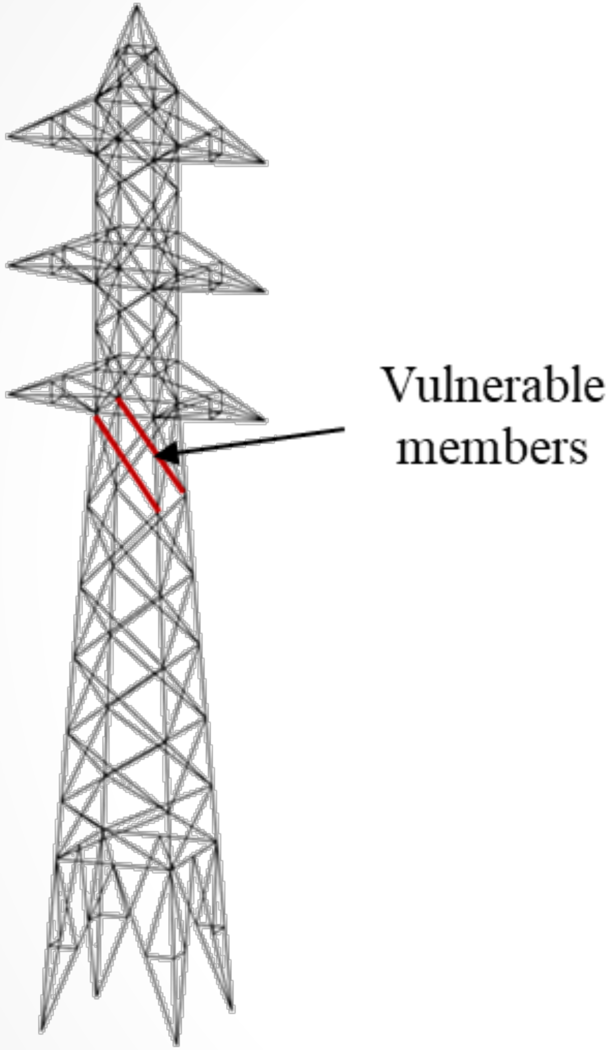


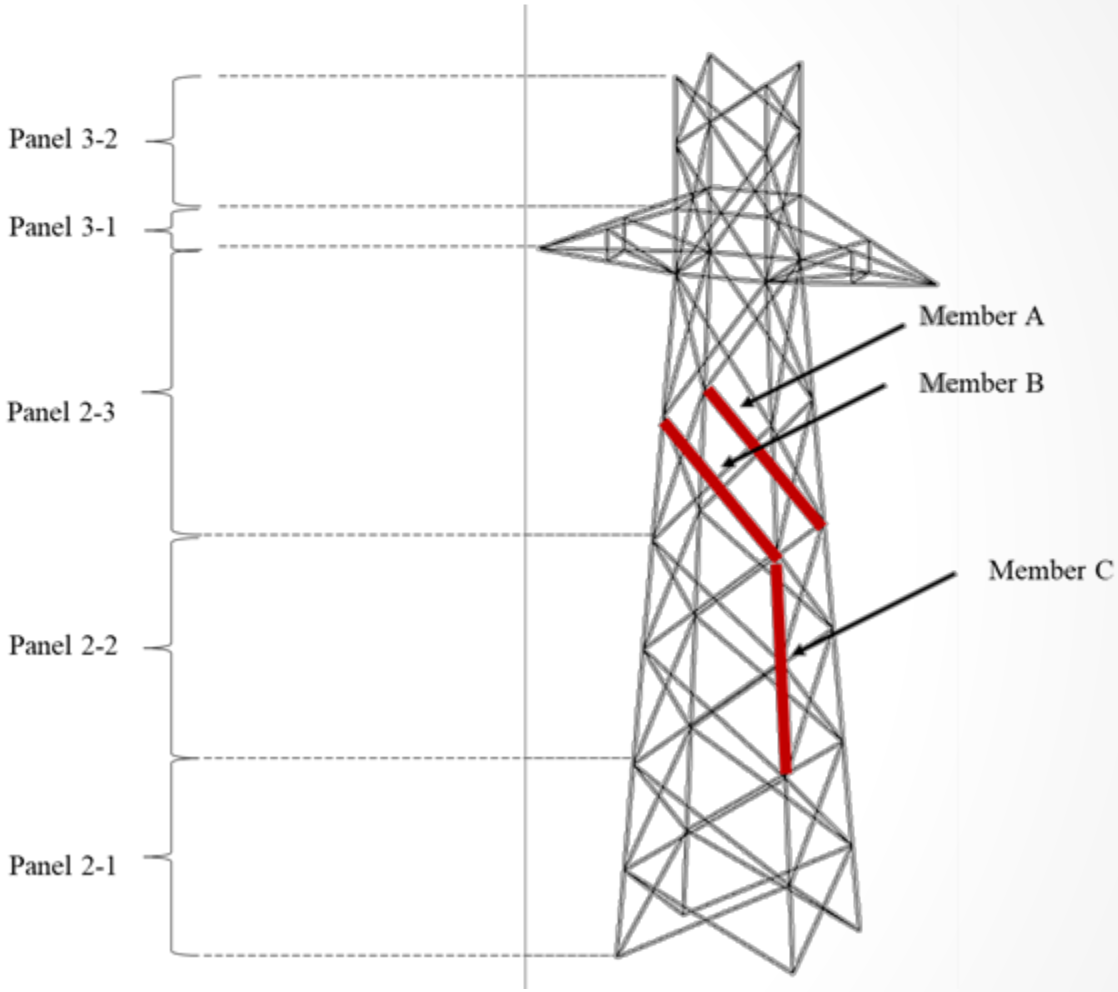




[Ma, Khazaali & Bocchini. Component-based fragility analysis of transmission towers subjected to hurricane wind load. *Engineering Structures* (242) 2021.]

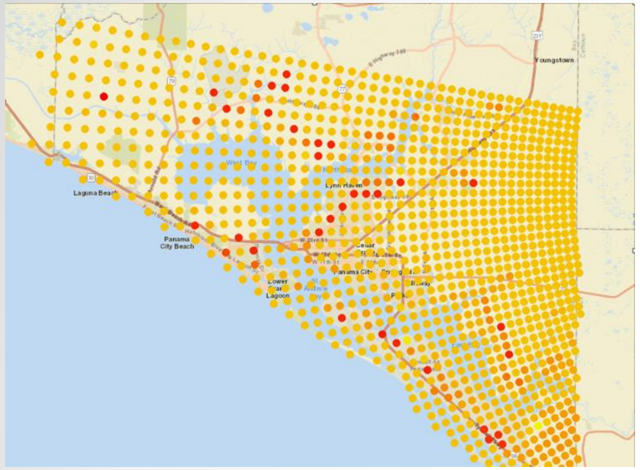
Tower Fragility: Progressive Collapse





[Ma, Khazaali & Bocchini. Component-based fragility analysis of transmission towers subjected to hurricane wind load. *Engineering Structures* (242) 2021.]

Topics of This Webinar

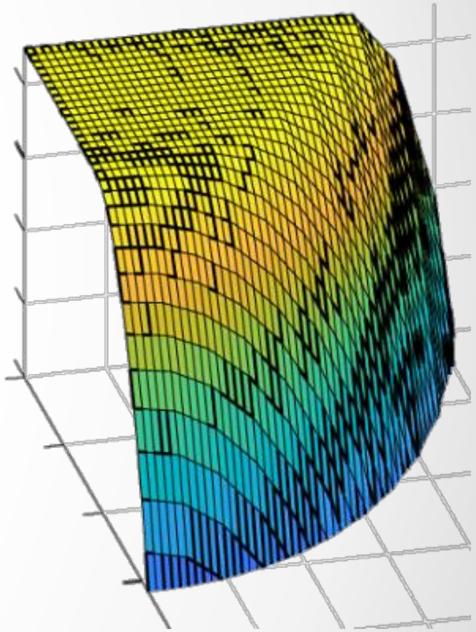


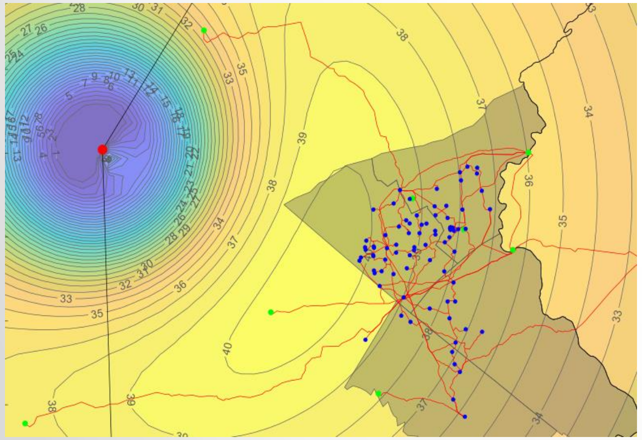
Approximation of the probability space: scenario selection

1

2

Approximation of the structural behavior: fragility models





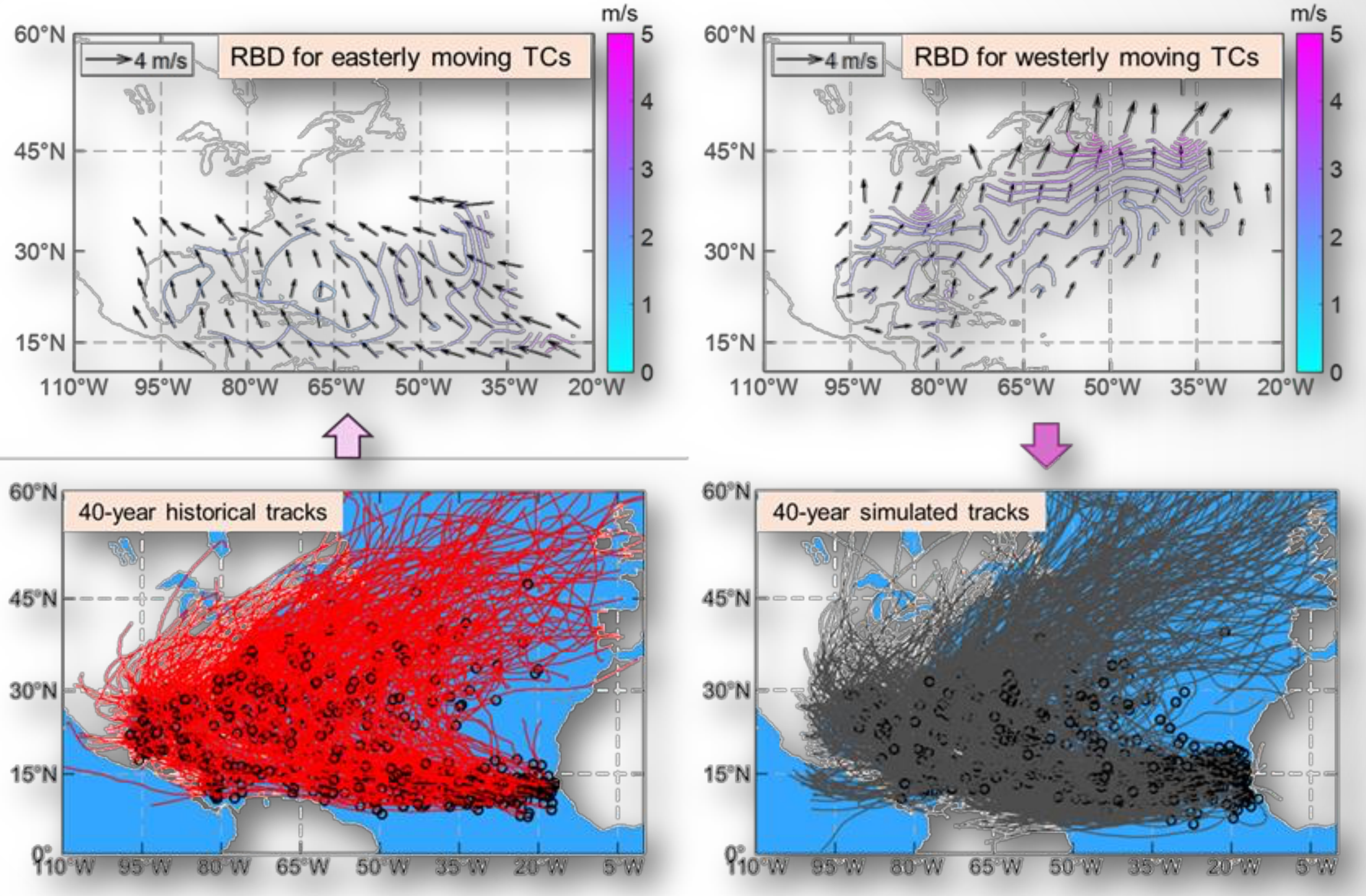
Approximation of the space and time domain: regional damage and recovery analysis

3

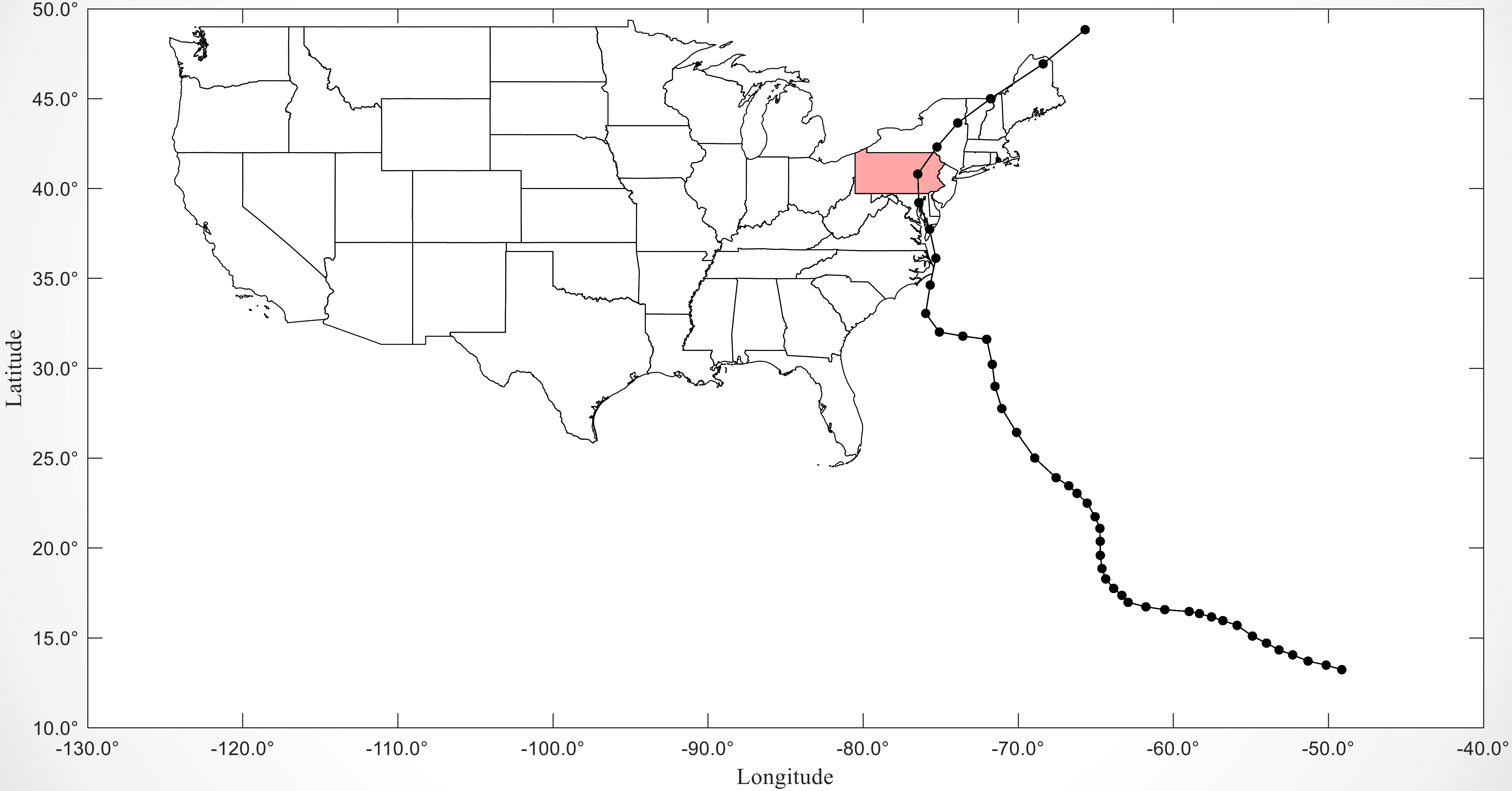
Hazard Model: Hurricane Simulation

[Sheng & Bocchini, An improved physics-based hurricane **track model** over North Atlantic basin with its application for wind hazard assessment, *under review*.]

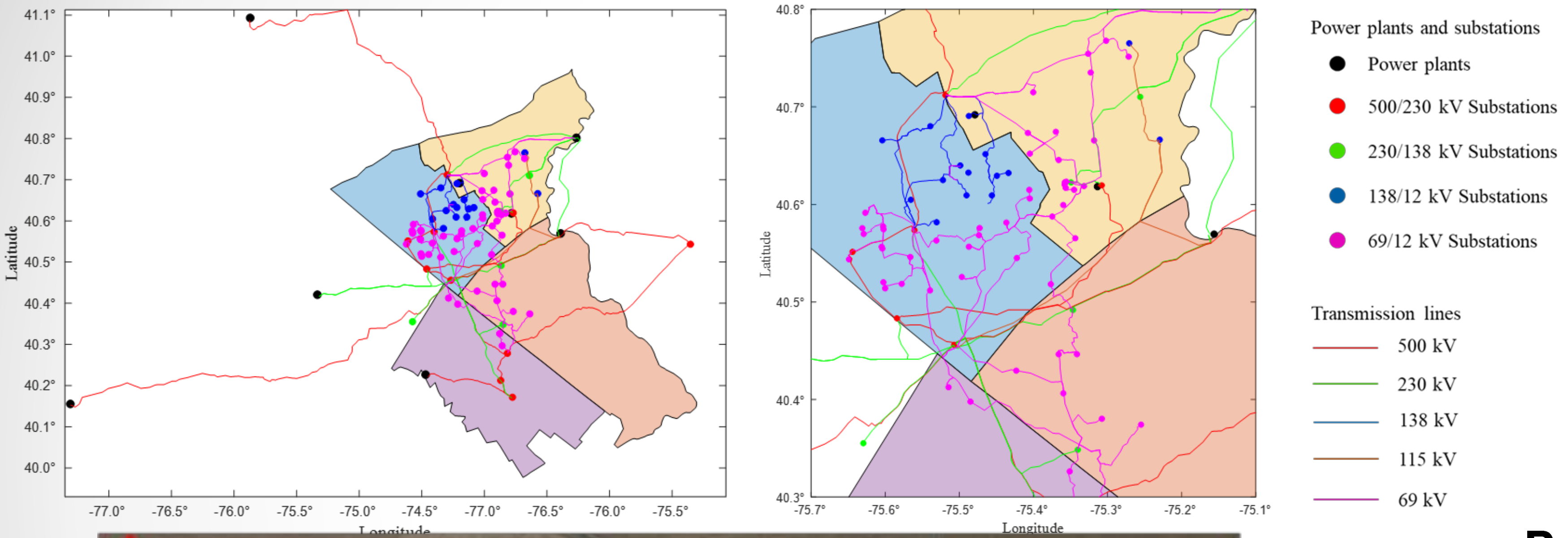
[Sheng & Bocchini, Characterization and statistical modelling of tropical cyclone **wind inflow angles** for joint wind and direction hazard assessment, *under review.*]

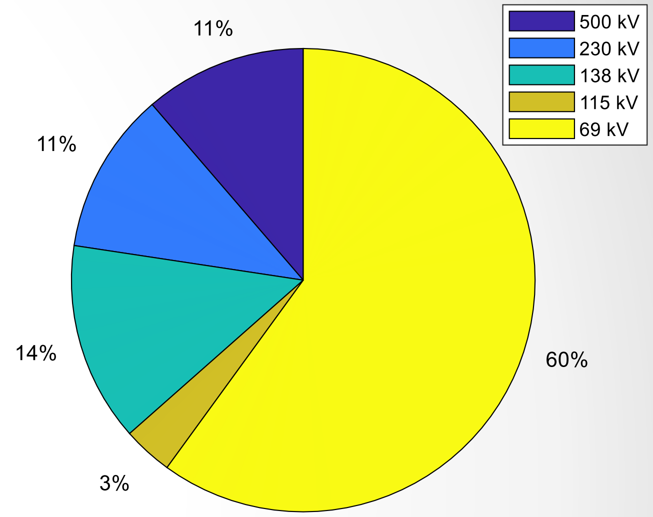


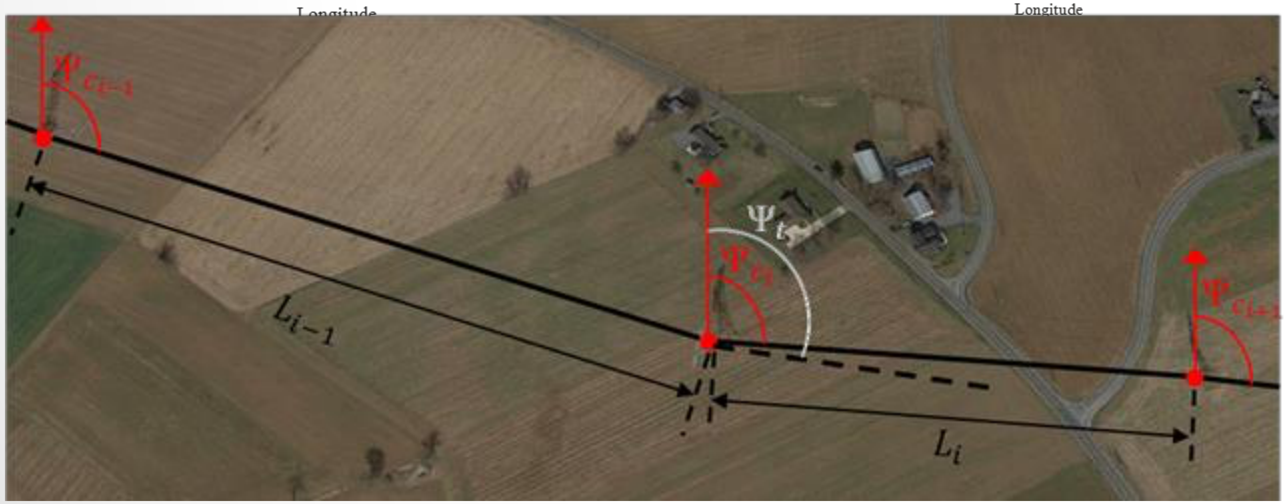
Hazard Model: Example Scenario



System Model







Power Network Statistics

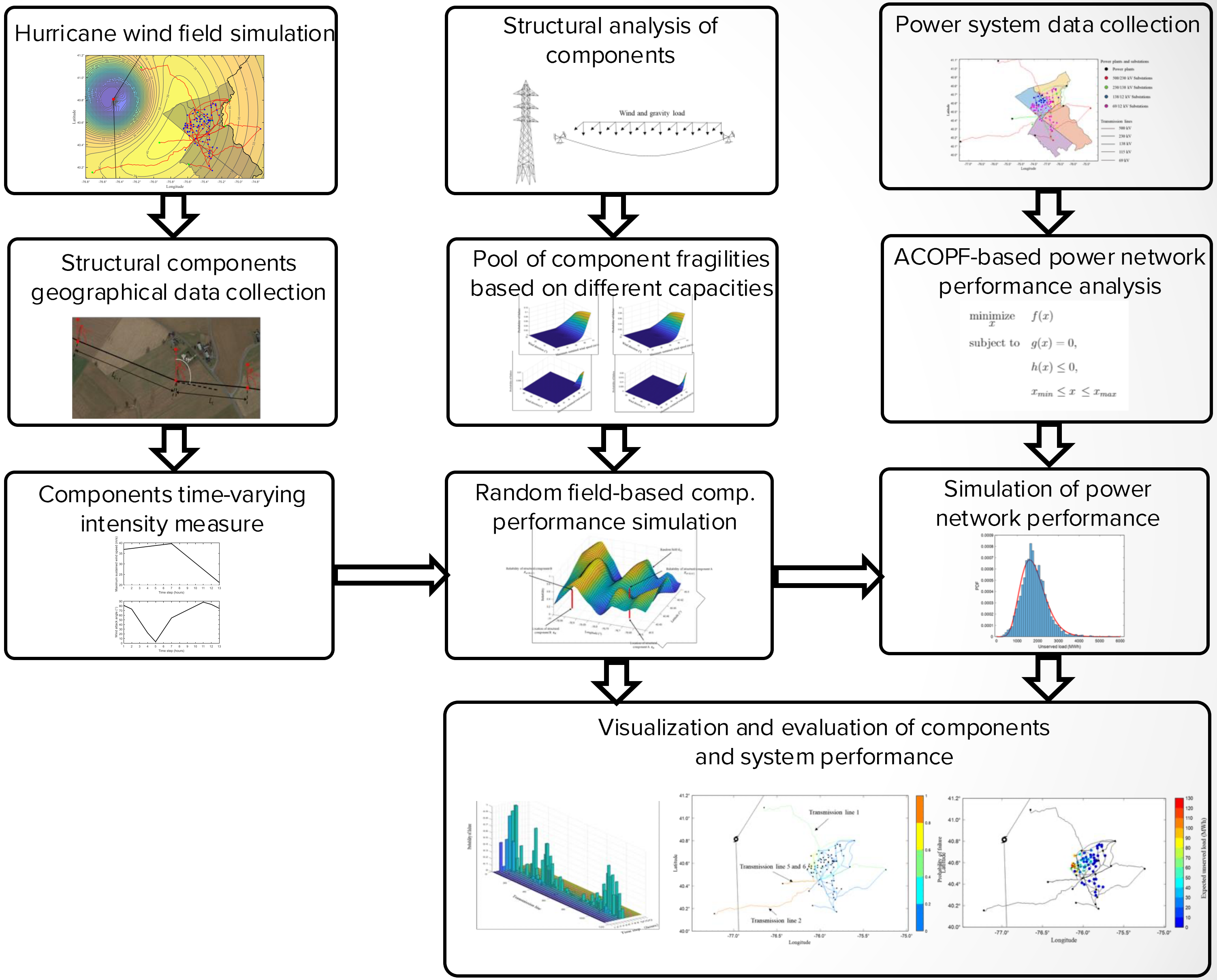
- 5,999 transmission towers
- 20,862 conductor segments
- 115 transmission lines
- 8 power plants
- 82 substations
- 313,803 households

[Ma, Christou, Bocchini. *Reliability Engineering & System Safety,* 2022.]

System Analysis

Global analysis framework

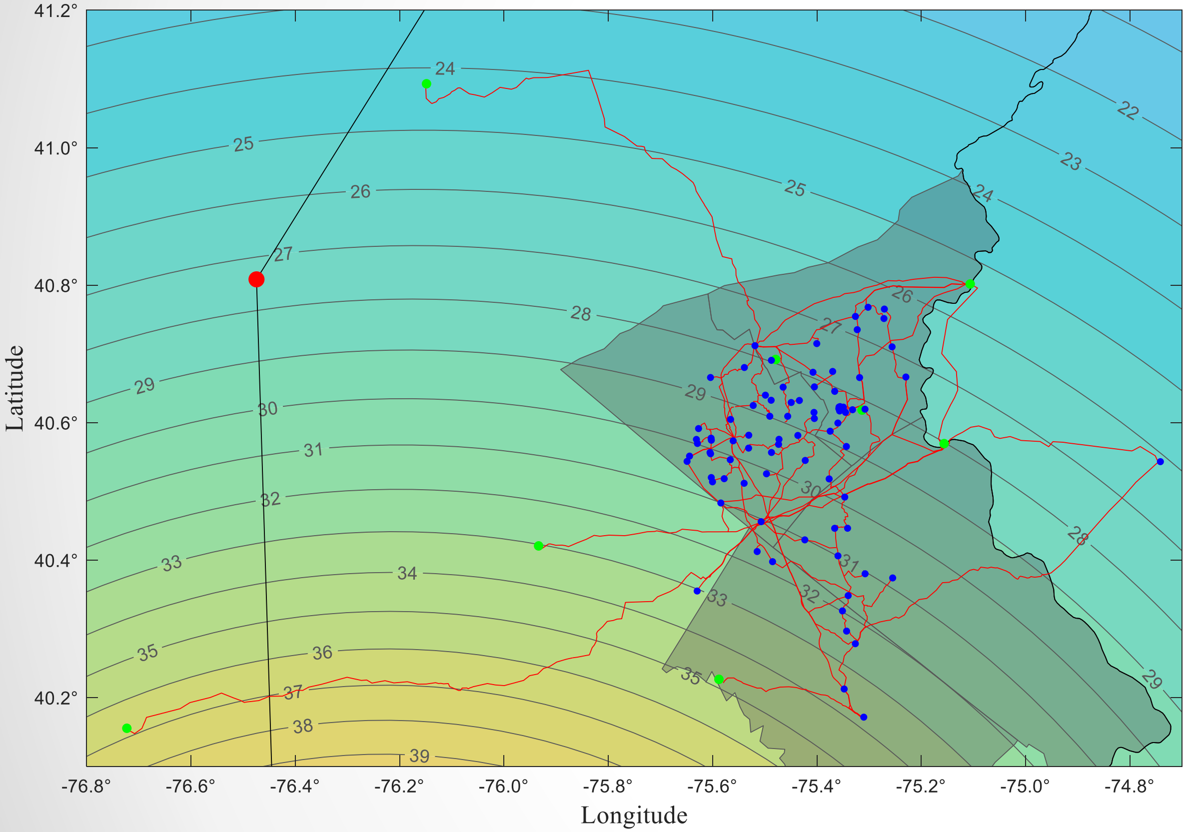
Important note: decouple uncertainty in capacity and demand



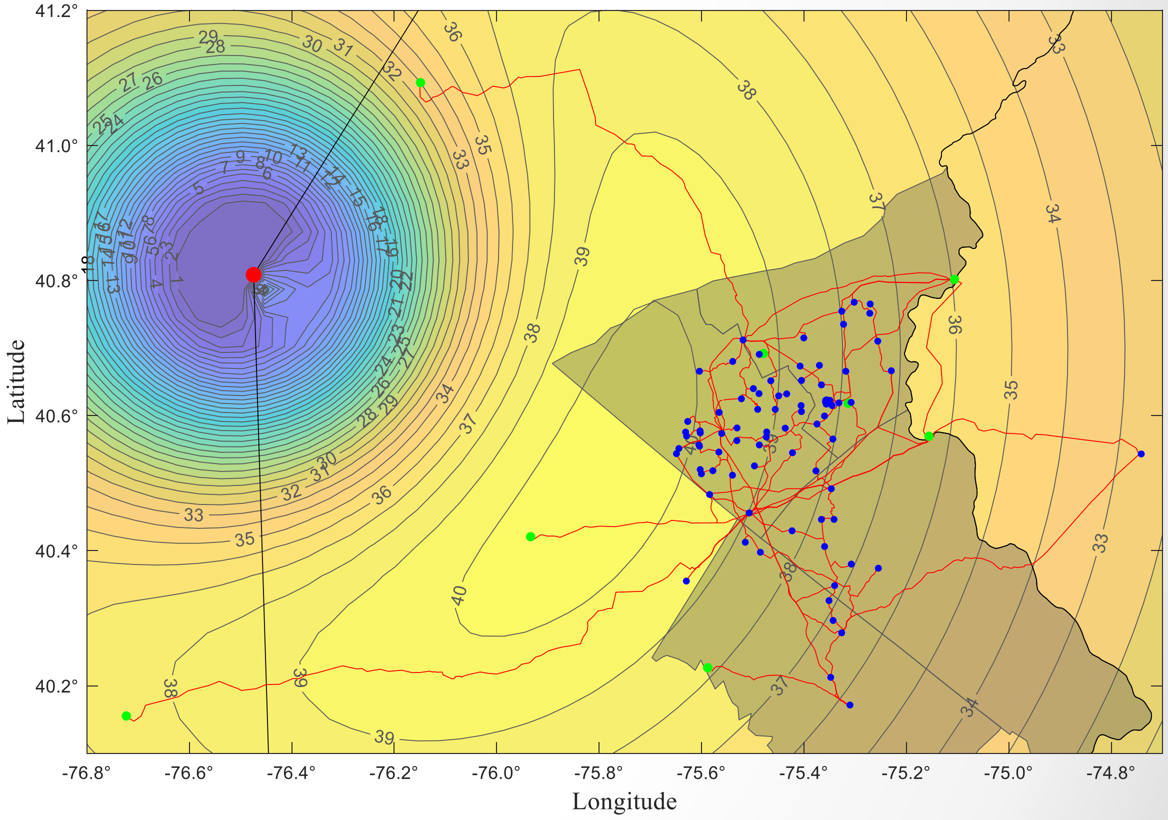
[Ma, Christou, *Bocchini, Reliability Engineering & System Safety*, 2022]

Hazard Model: Example Scenario

Wind speed field at t_1

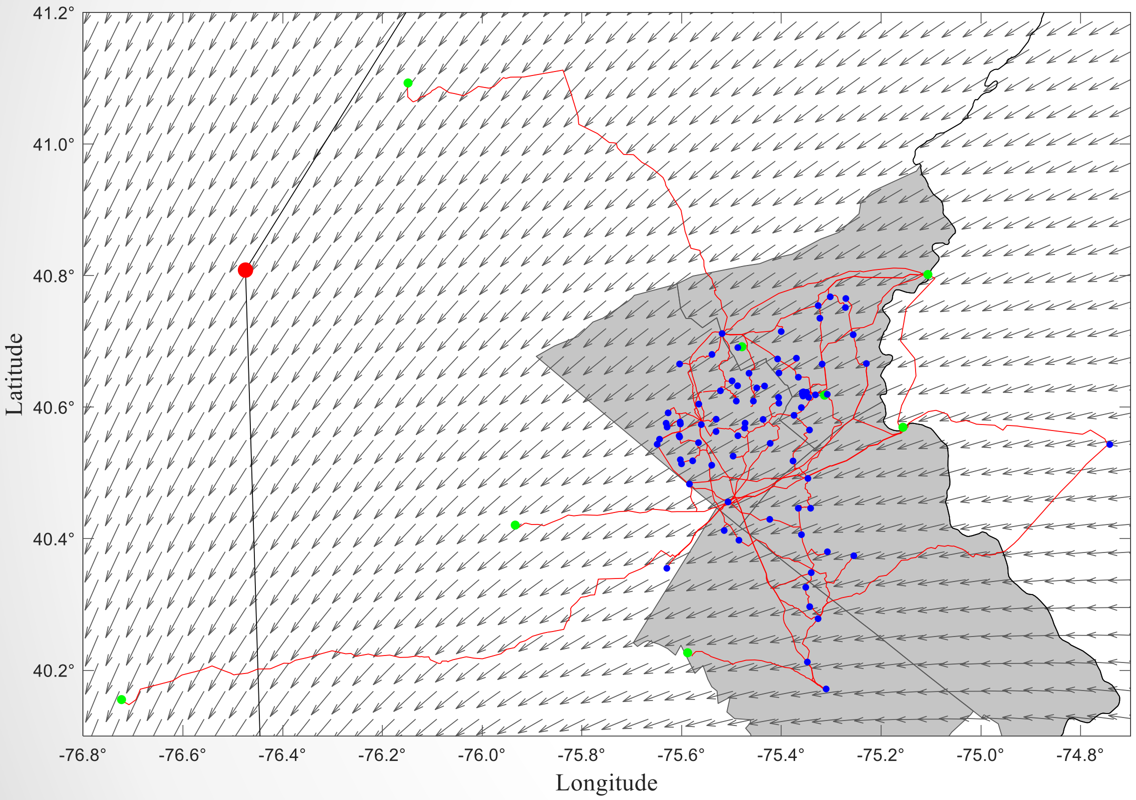


Wind speed field at t_7

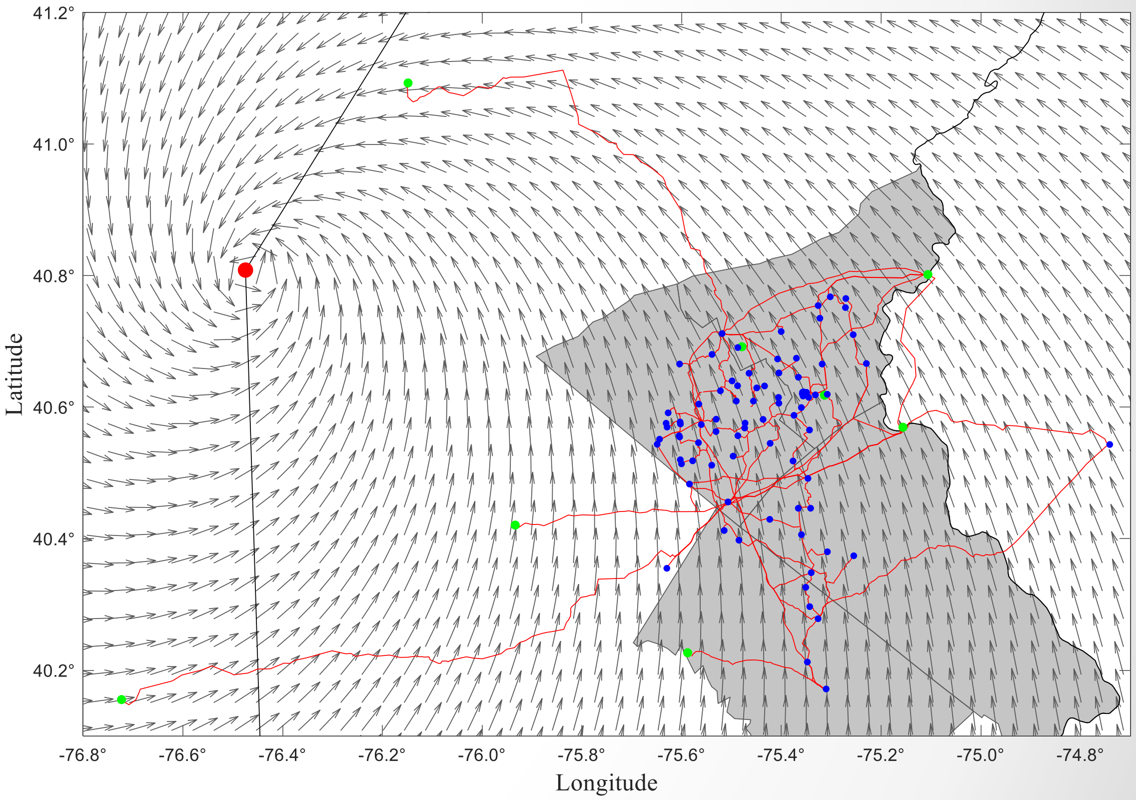


Hazard Model: Example Scenario

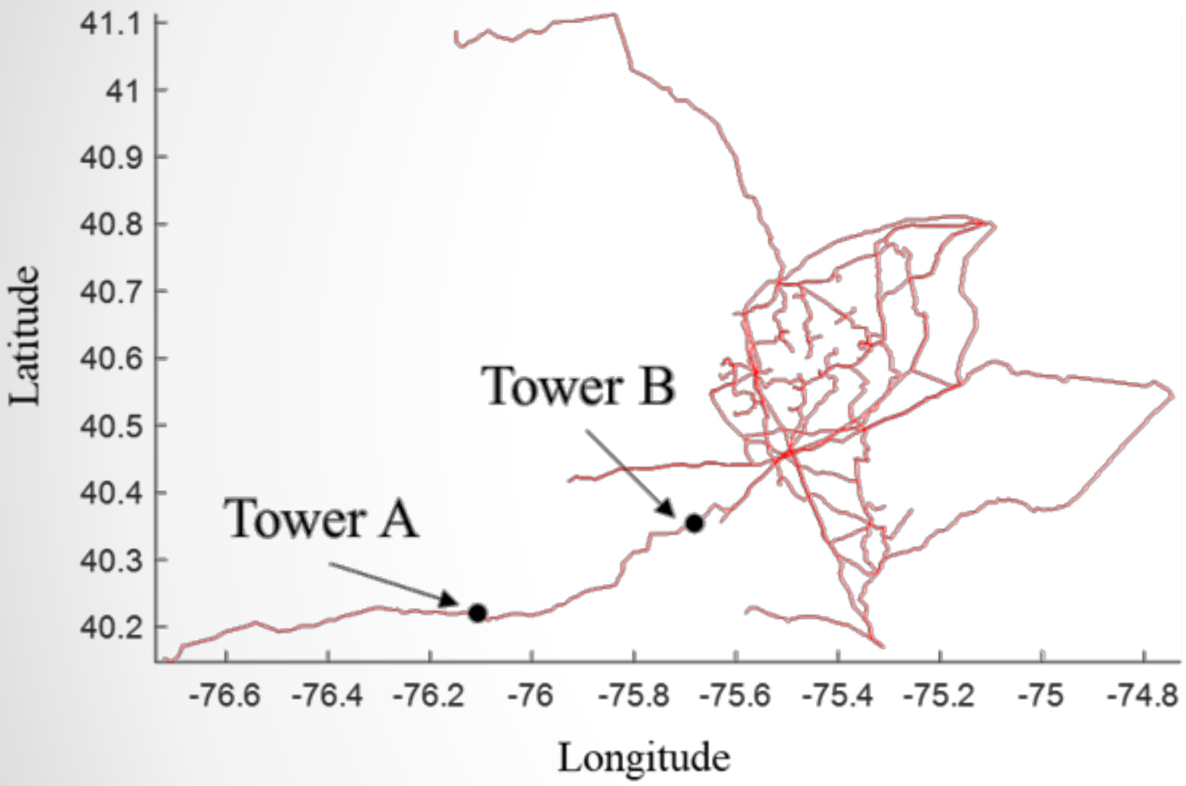
Wind direction field at t_1

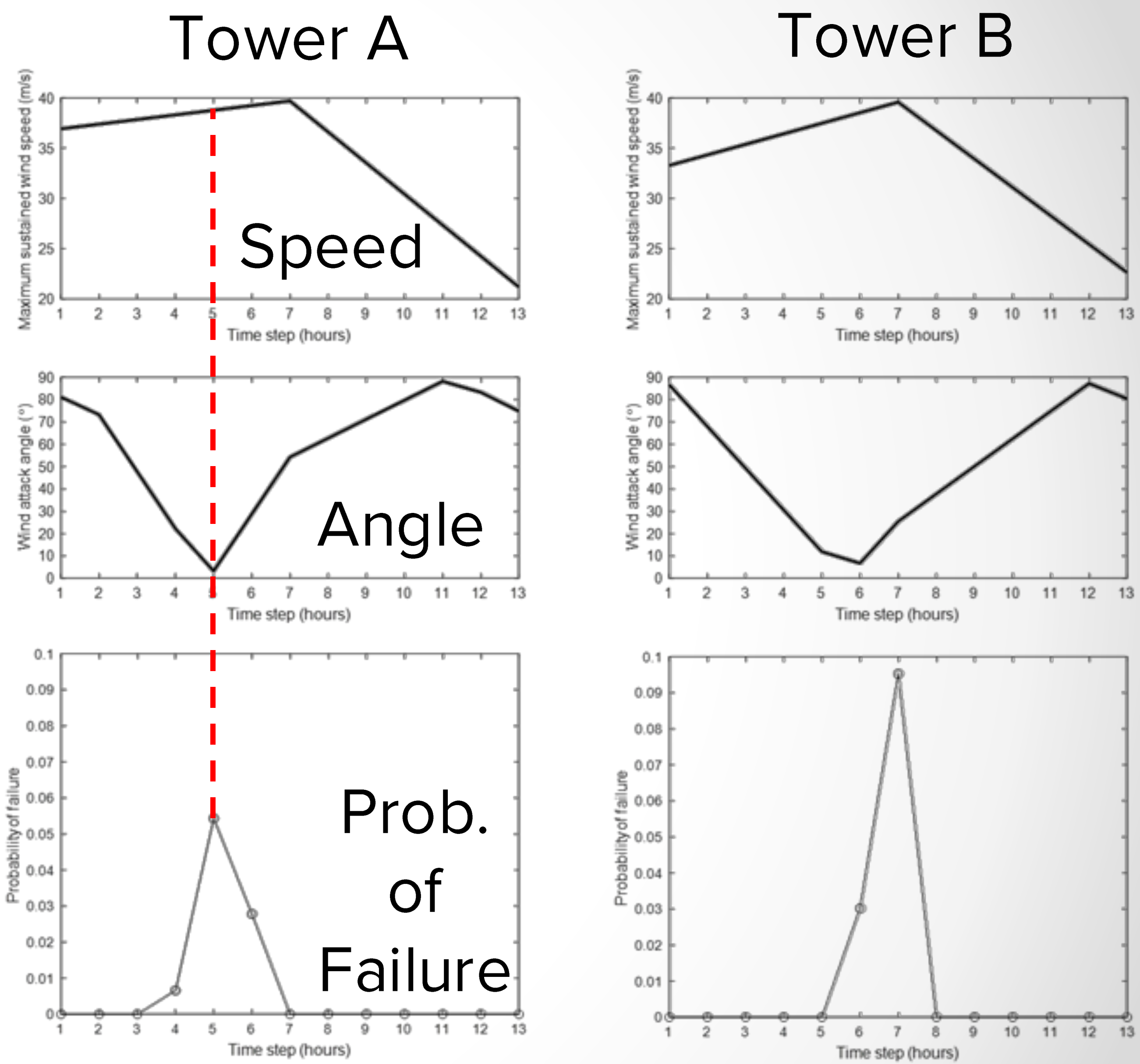


Wind direction field at t_7

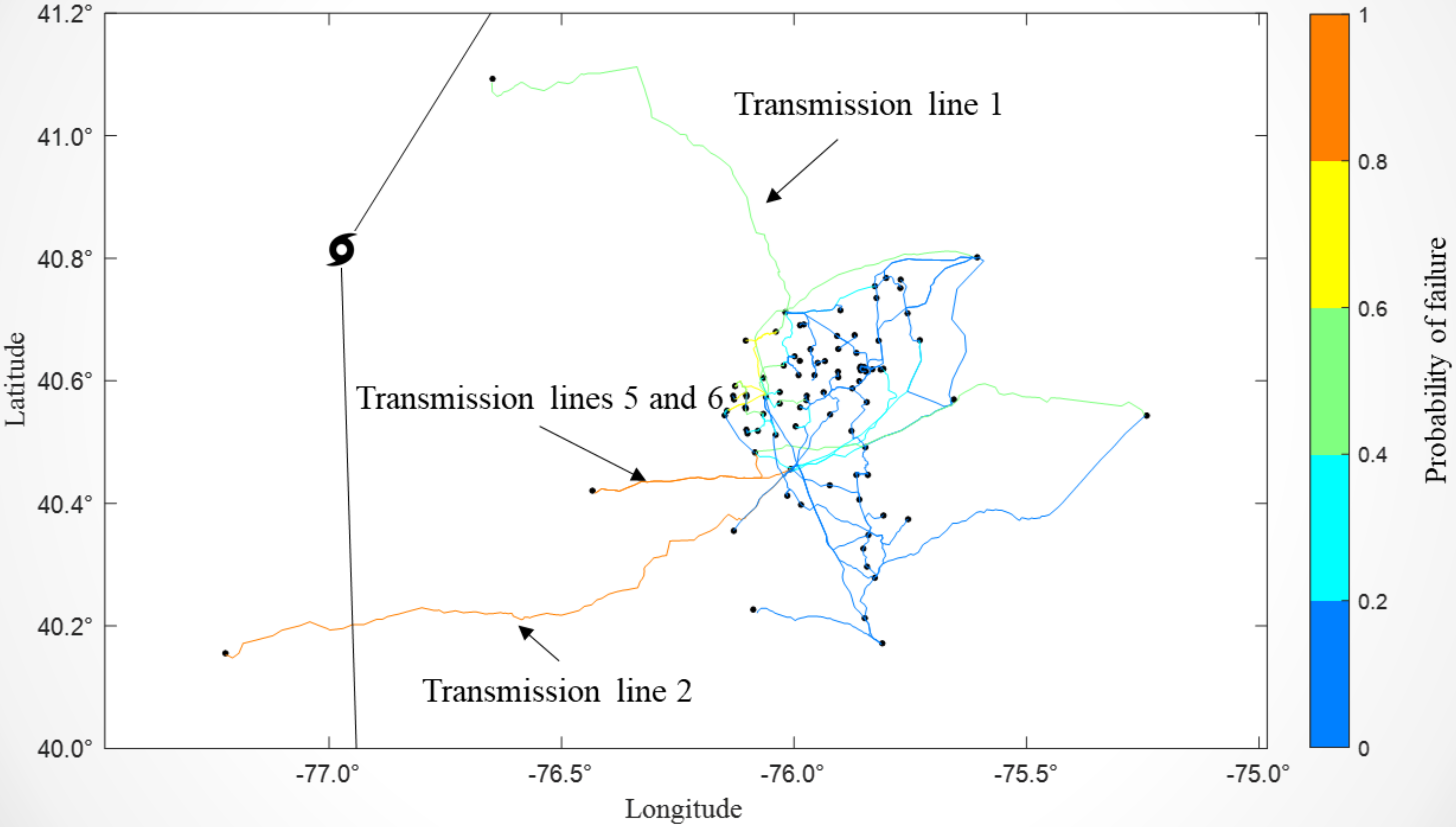


System Reliability

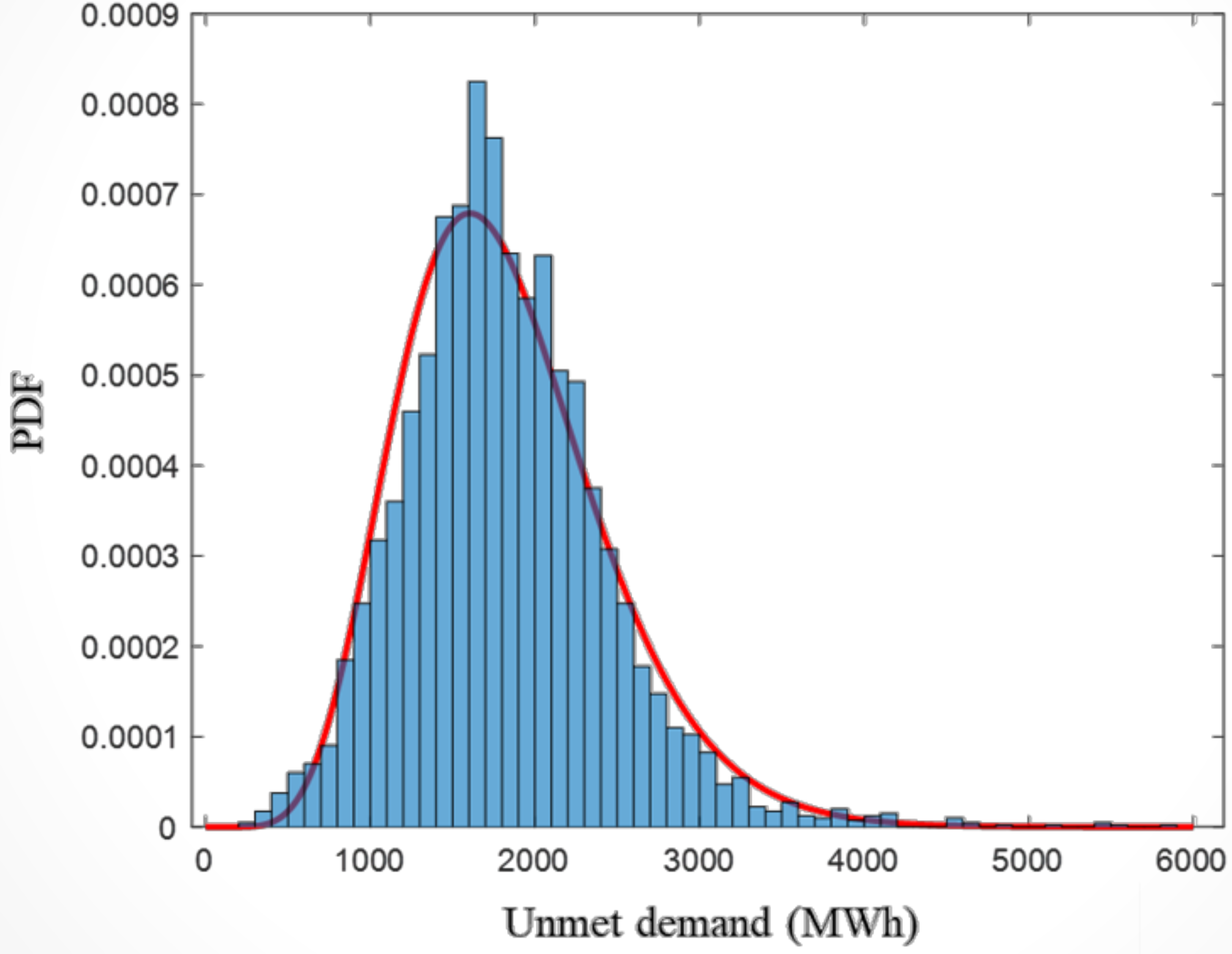




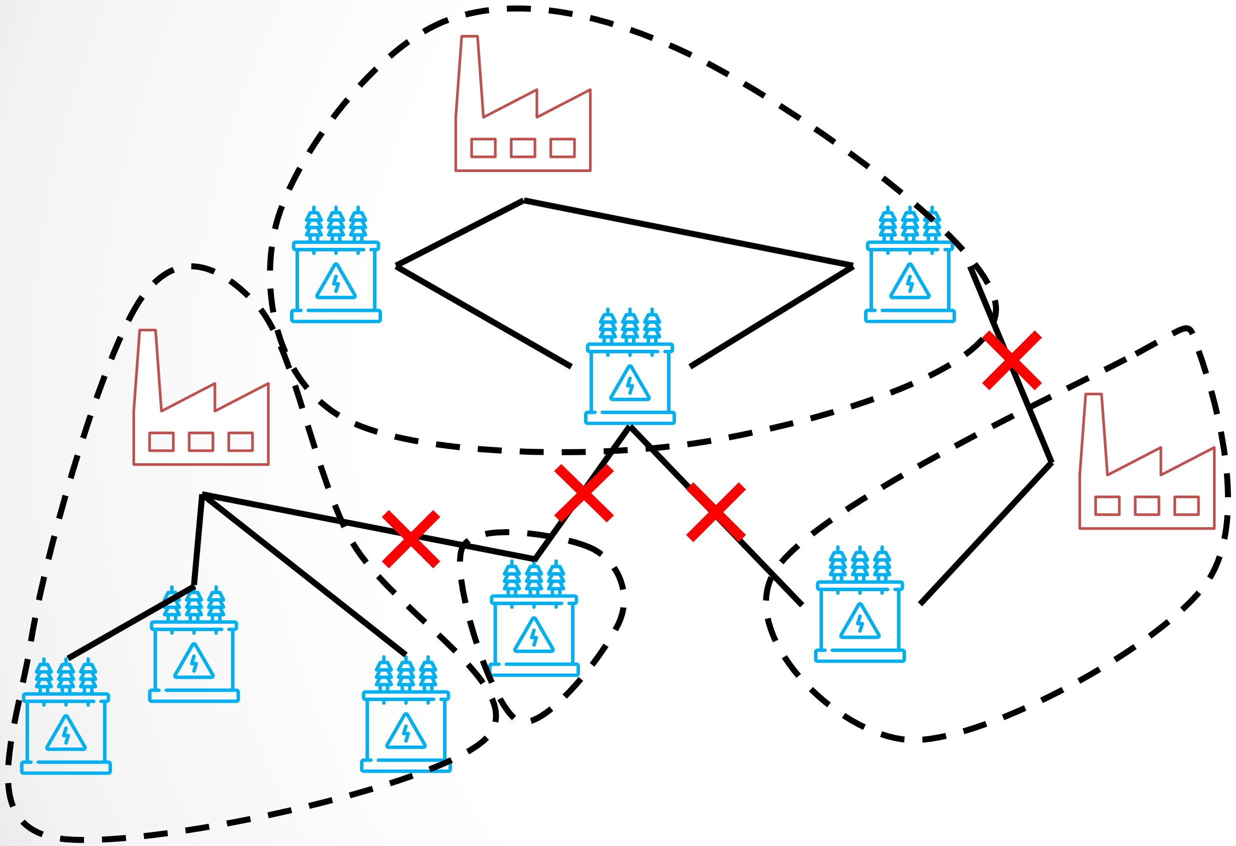
System Functionality



System Functionality



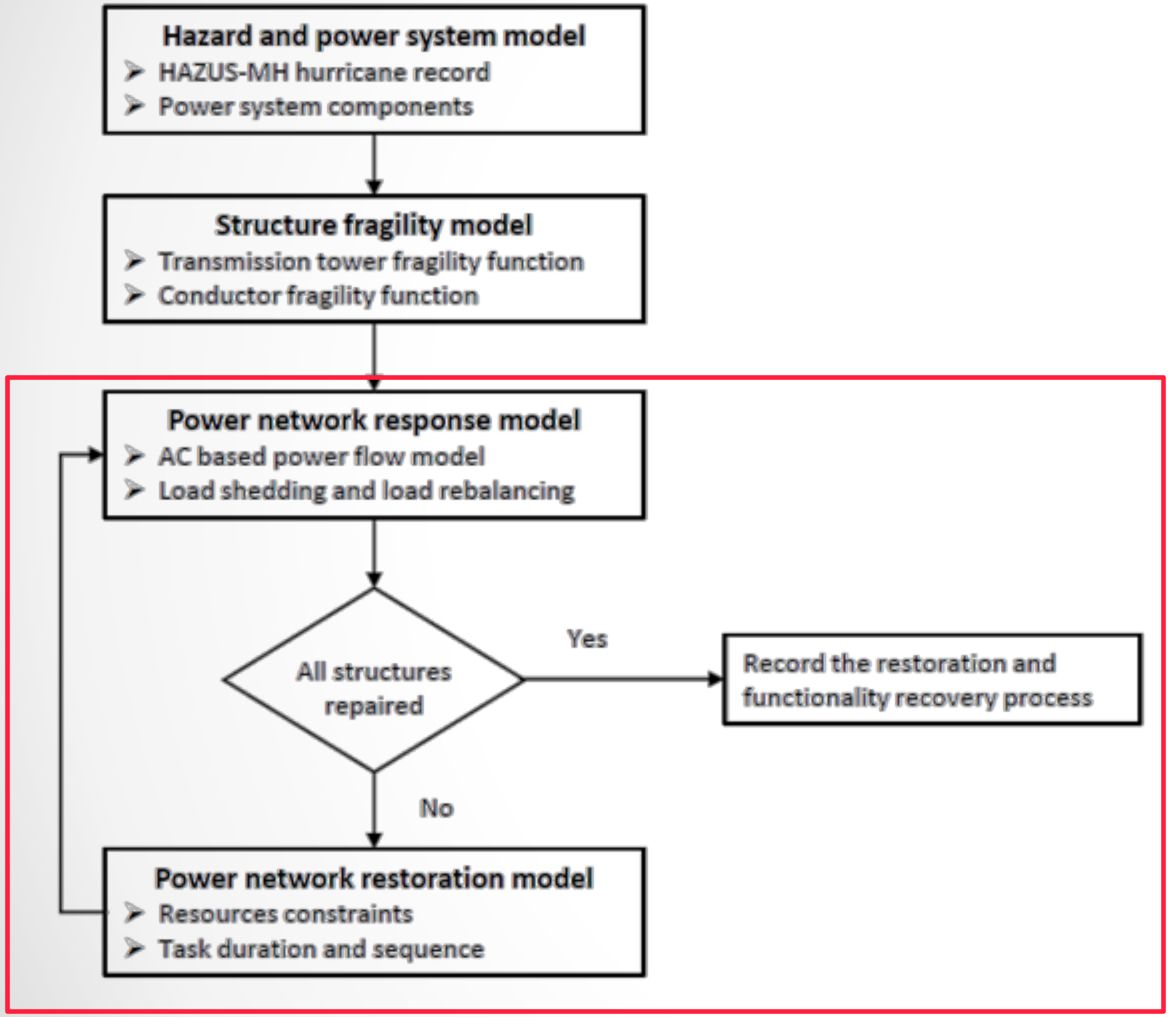
System Recovery

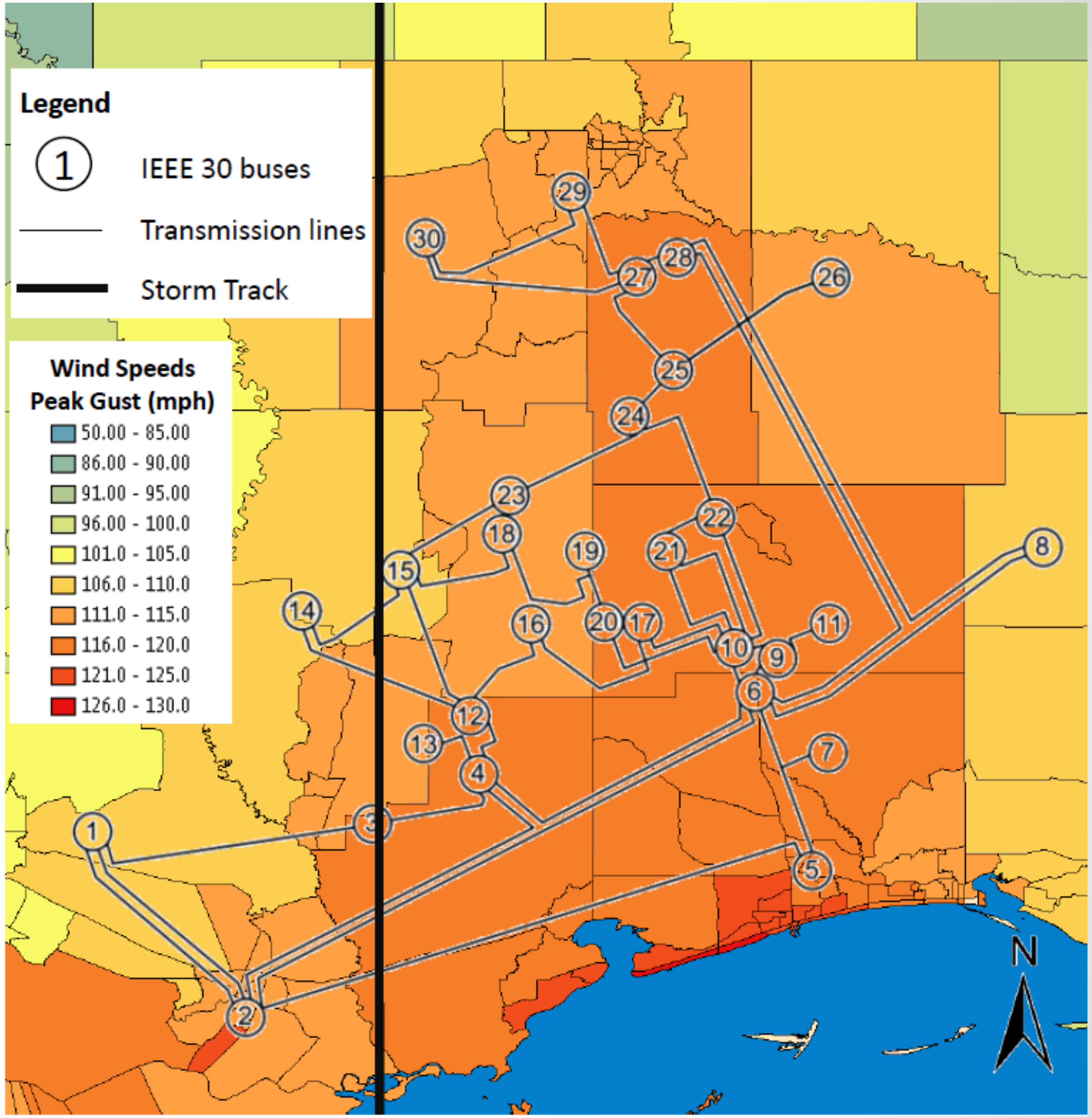


Algorithm

1. Remove failed lines according to structural failure model
2. Determine sub-grids
3. Check generator in sub-grids and perform ACOPF
4. Load shedding
5. Compute unmet demand for the network

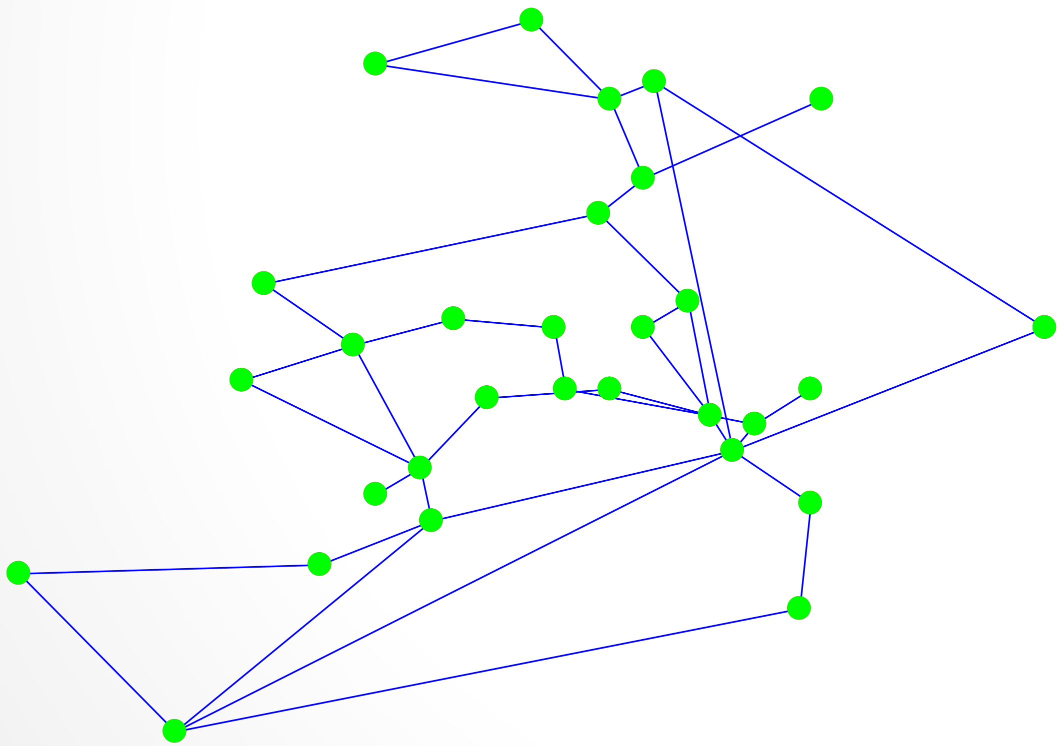
System Recovery

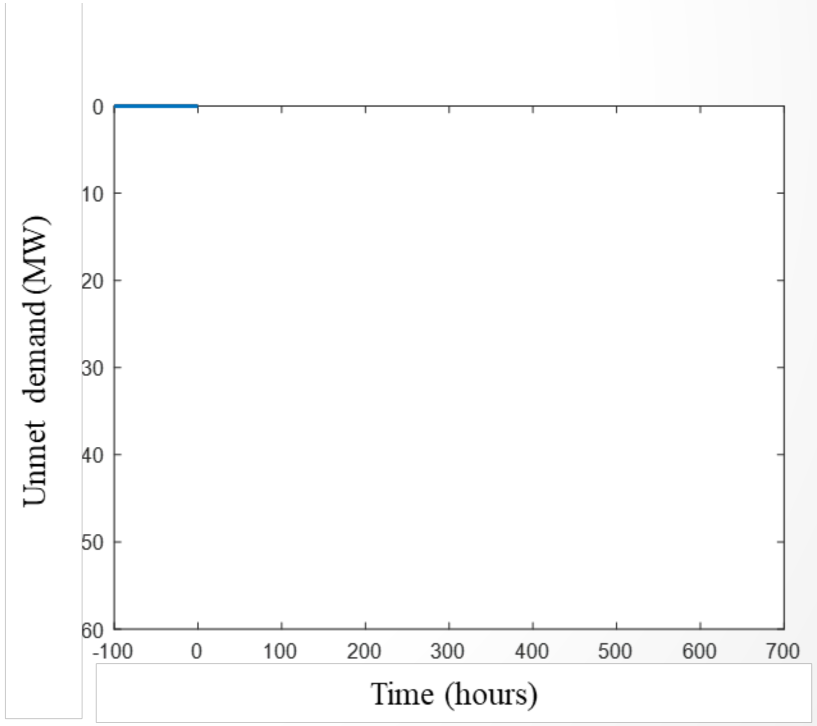




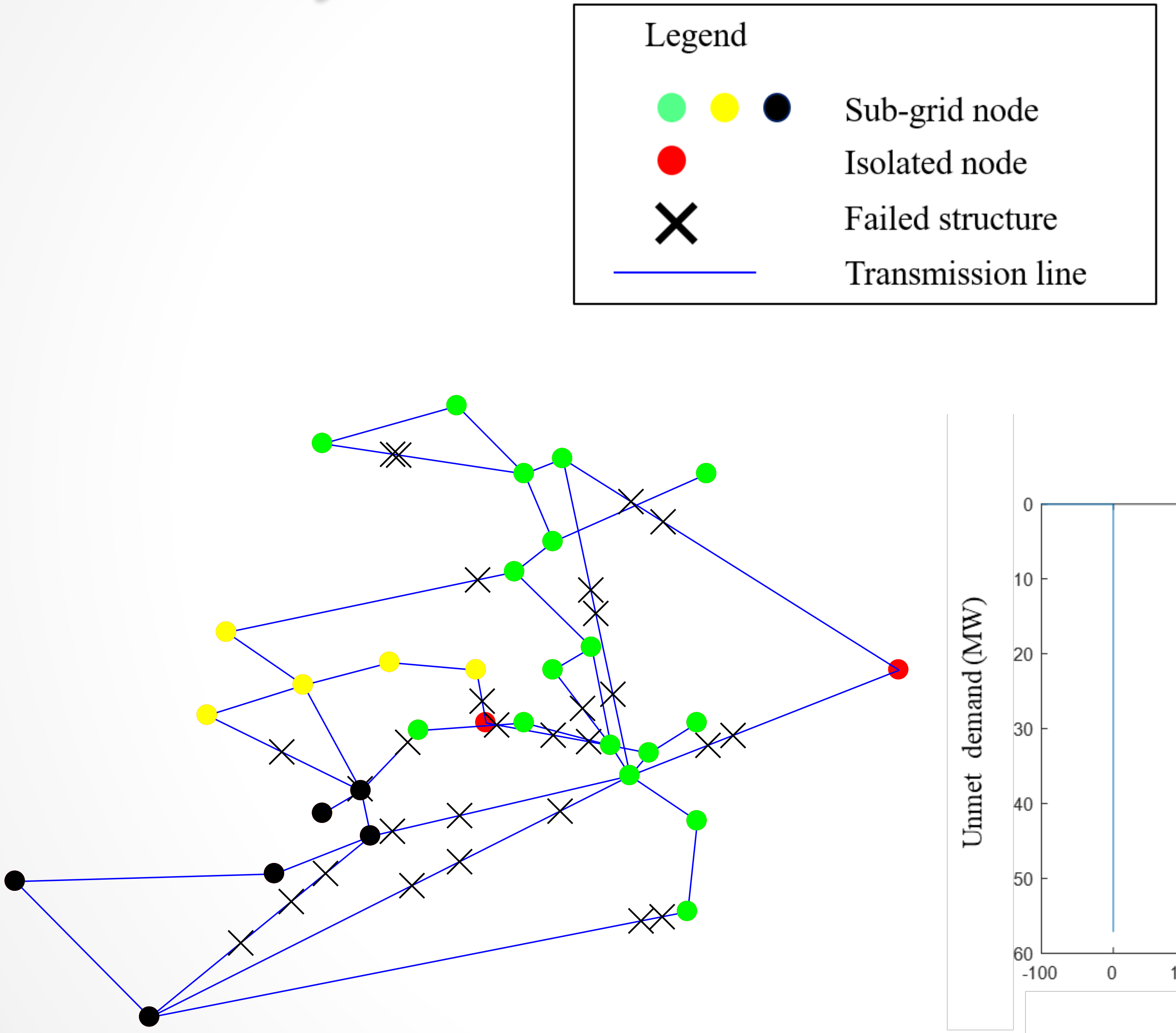
System Recovery

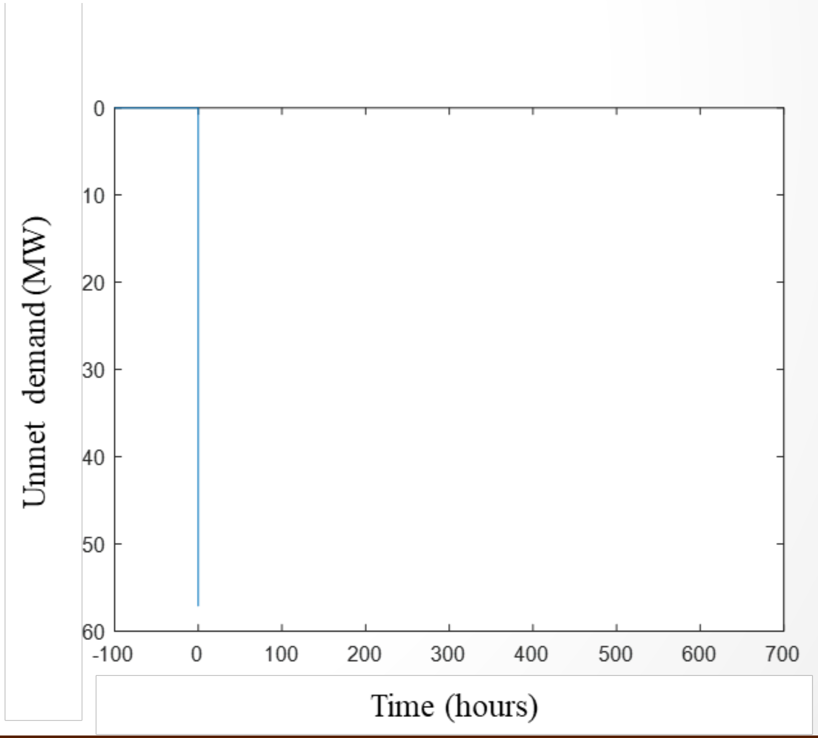
Legend	
(green, yellow, black dots)	Sub-grid node
(red dot)	Isolated node
✕	Failed structure
(blue line)	Transmission line



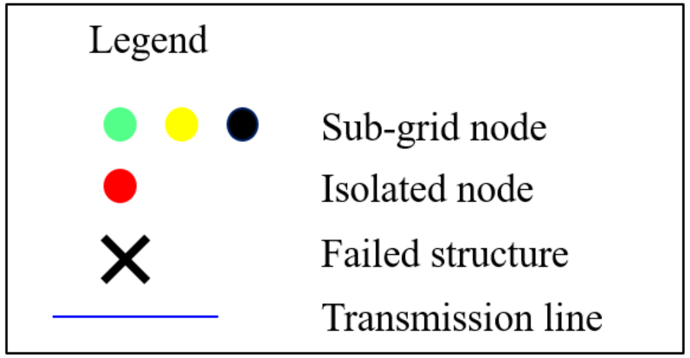


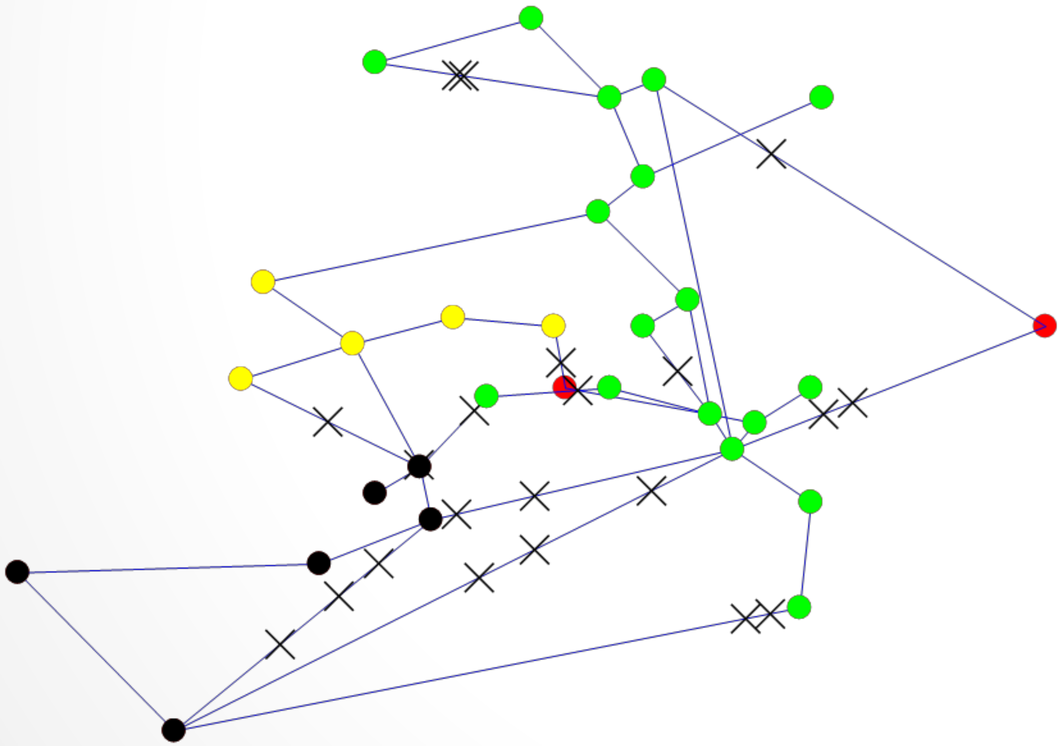
System Recovery

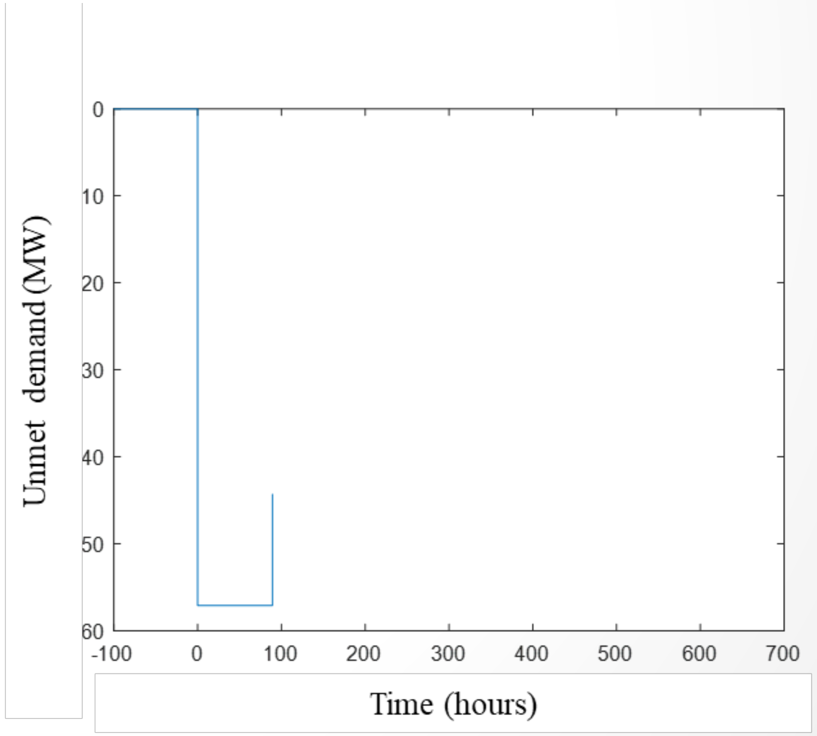




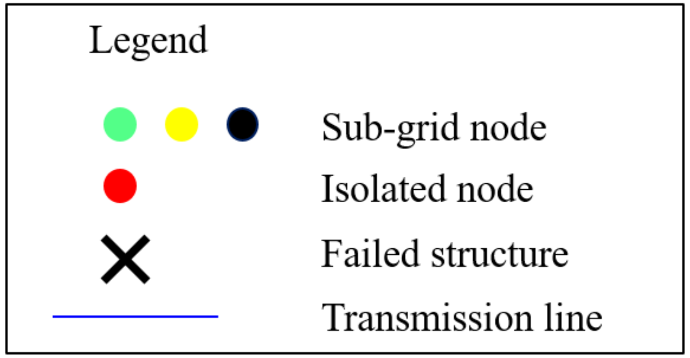
System Recovery

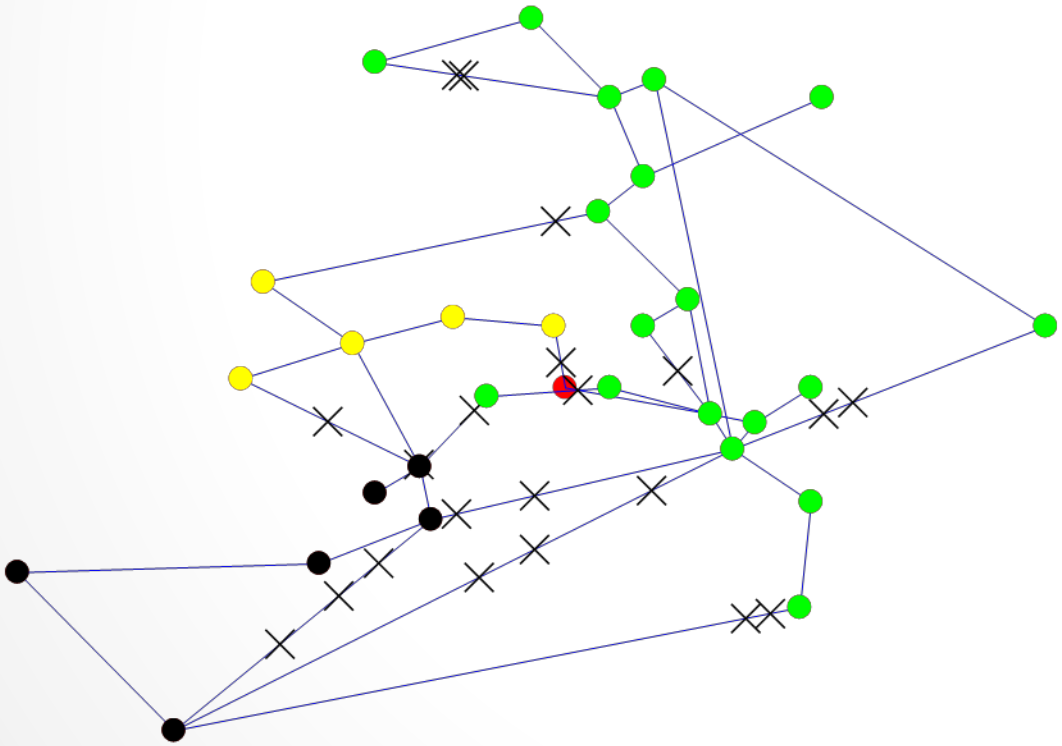


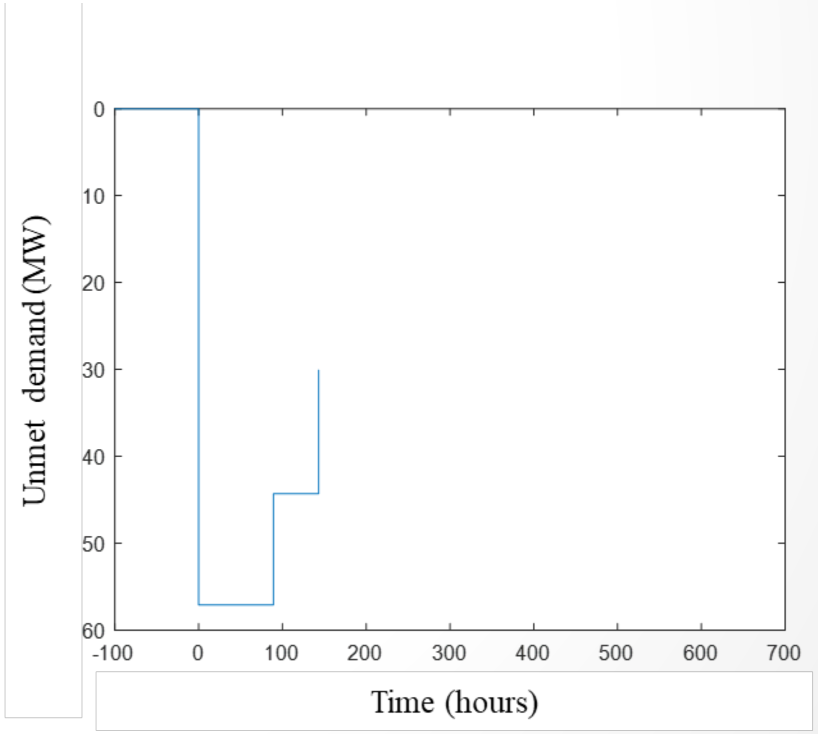




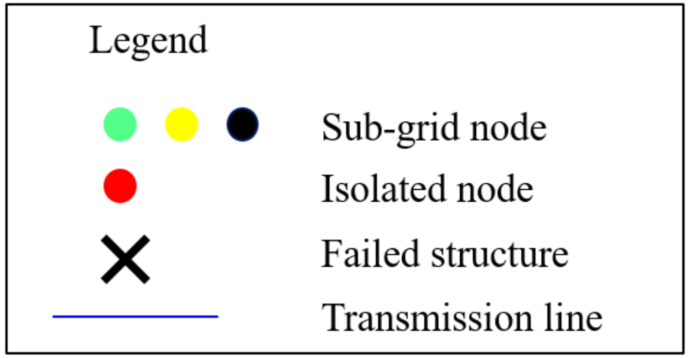
System Recovery

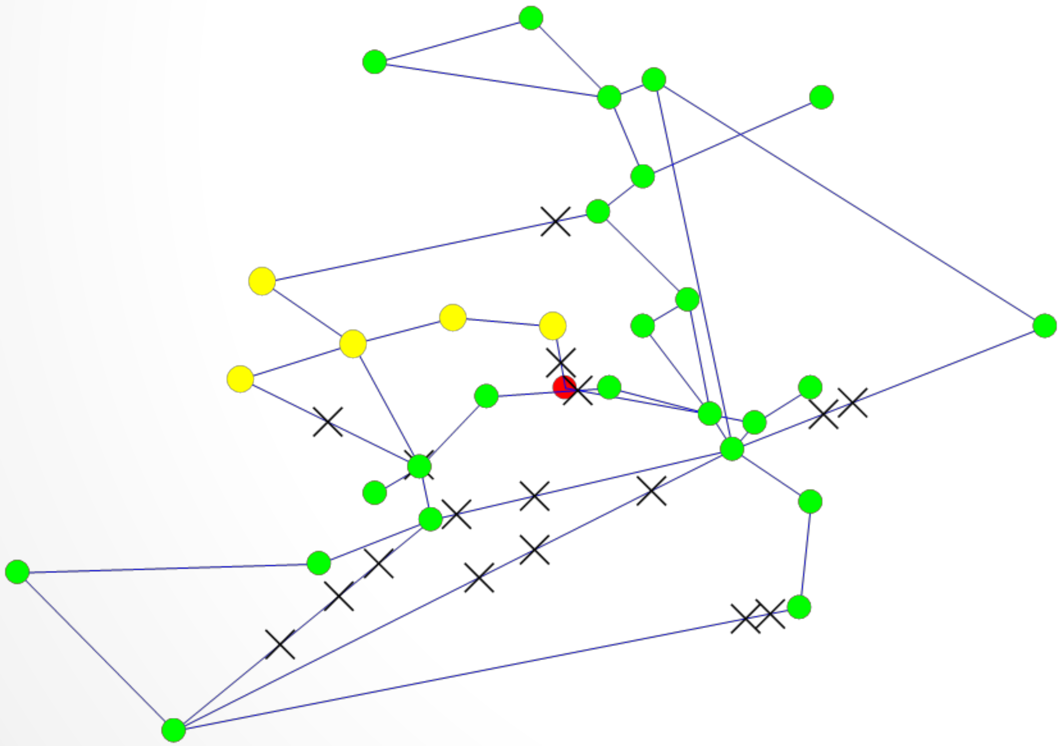


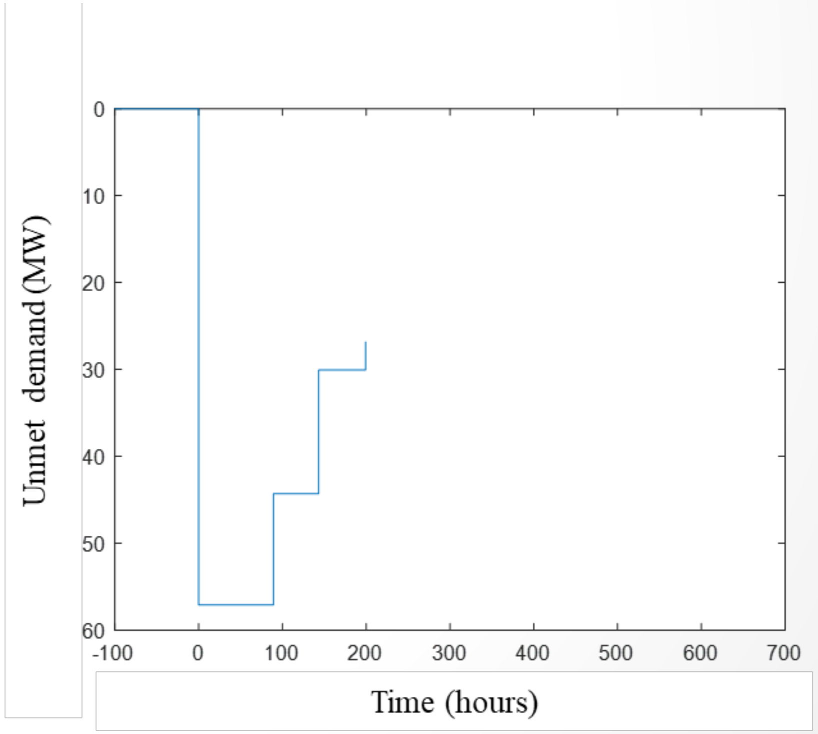




System Recovery







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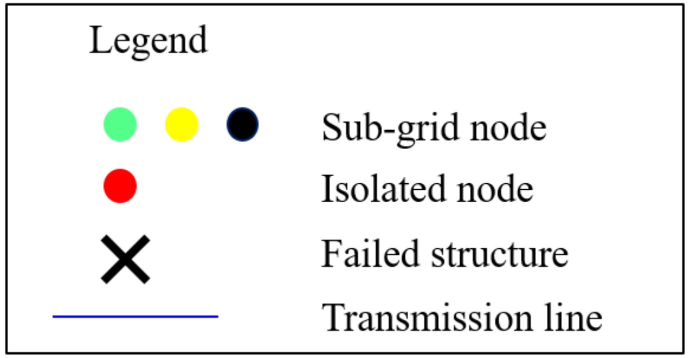

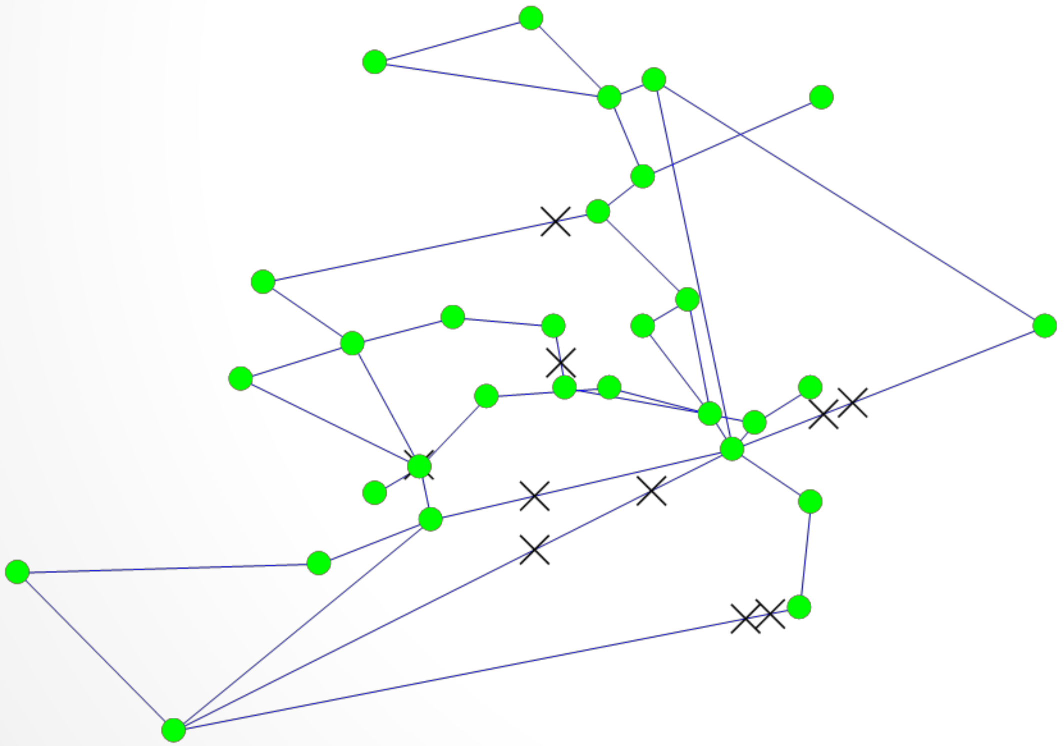

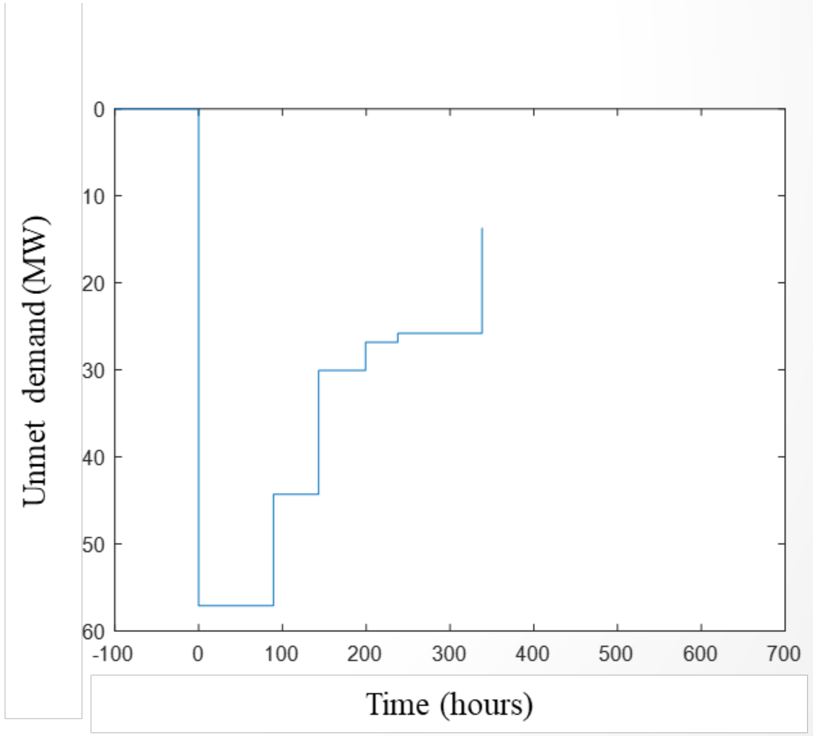

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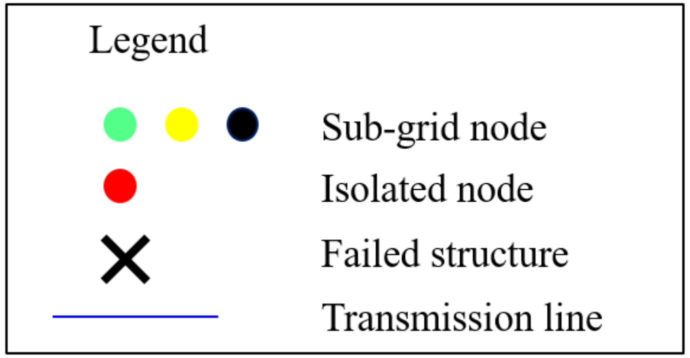

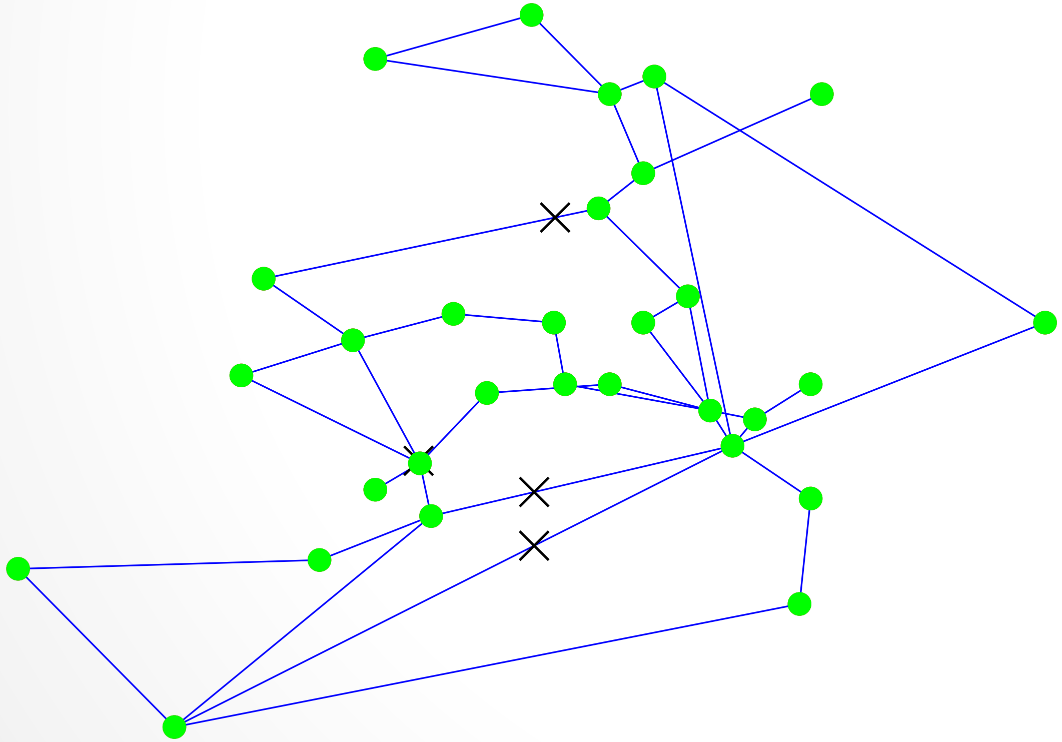

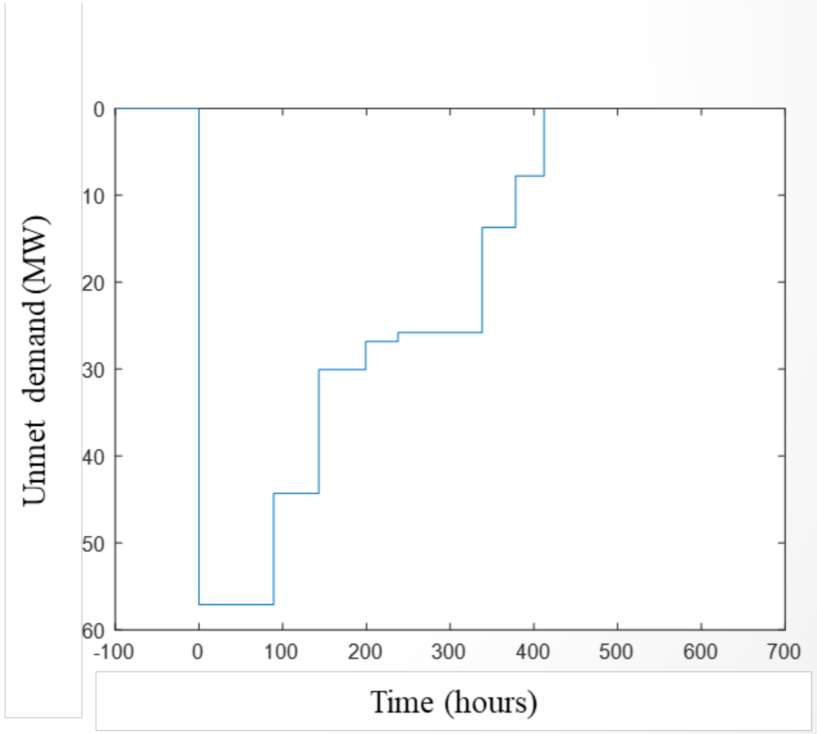

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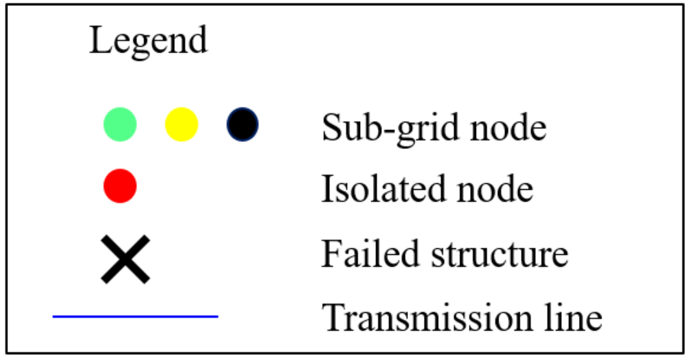
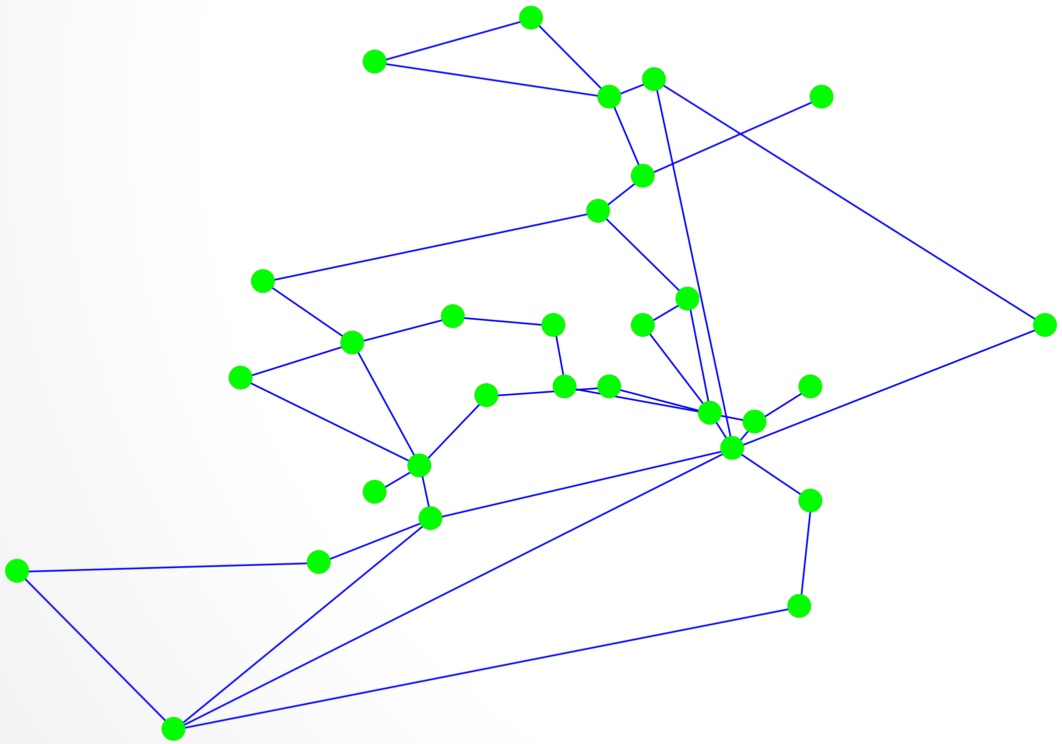
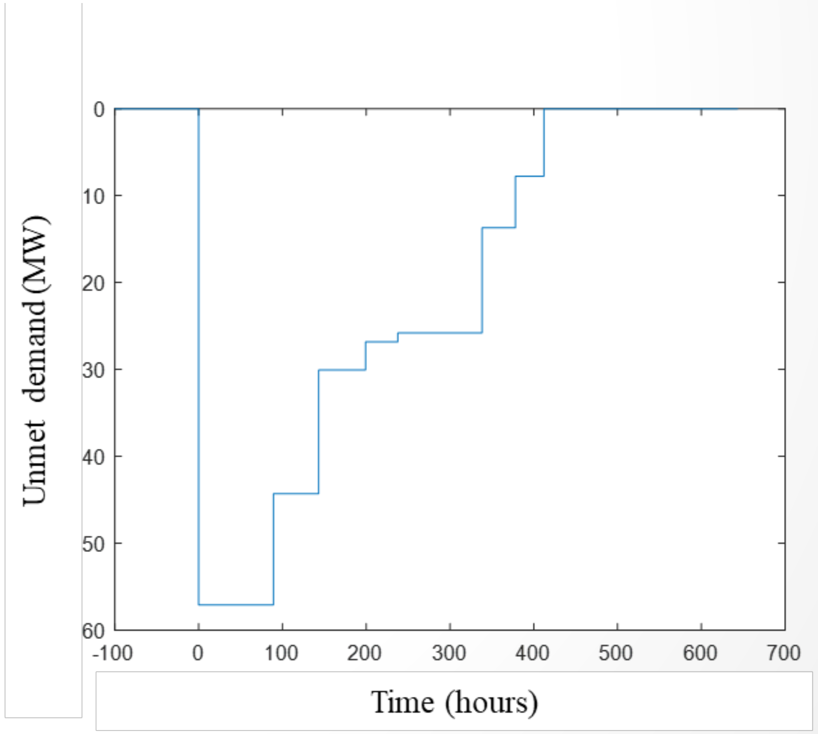
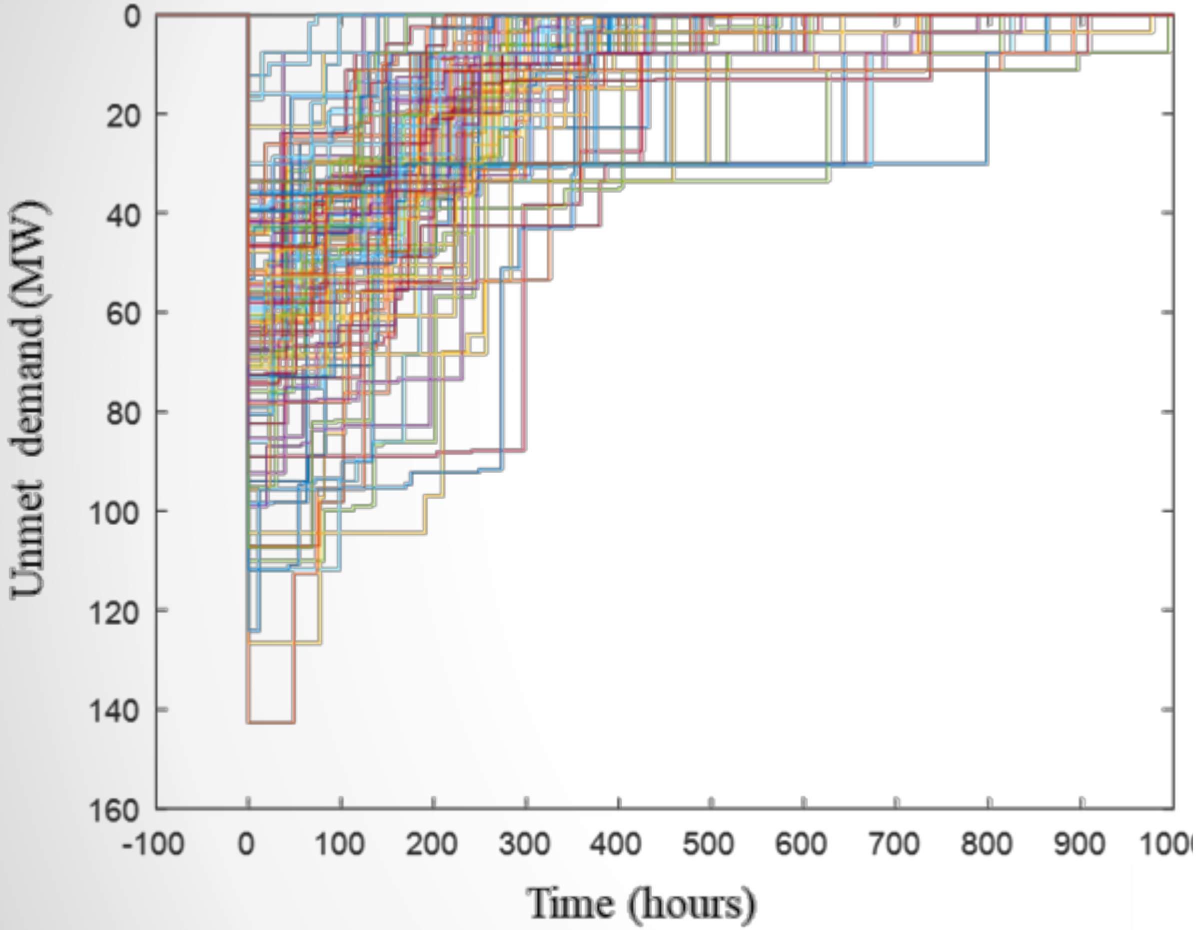
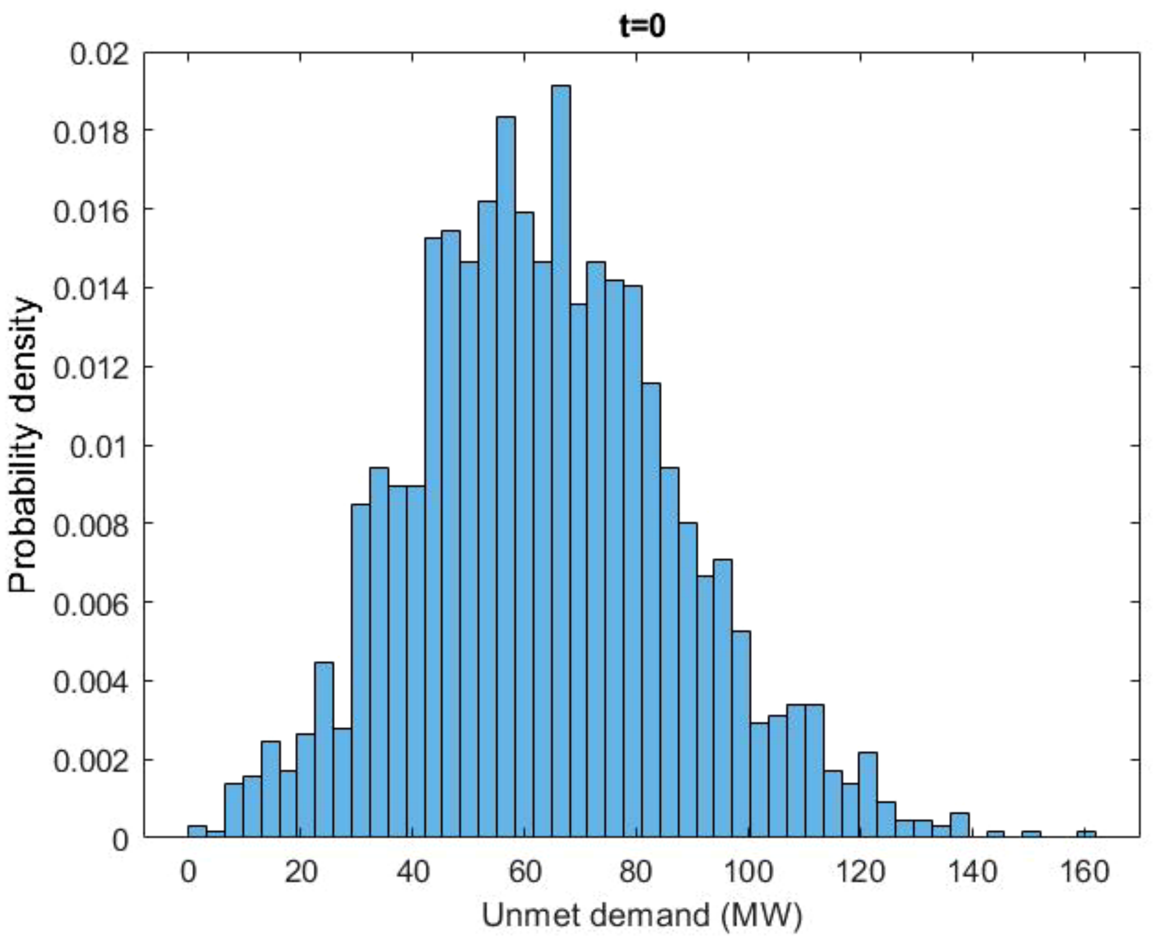


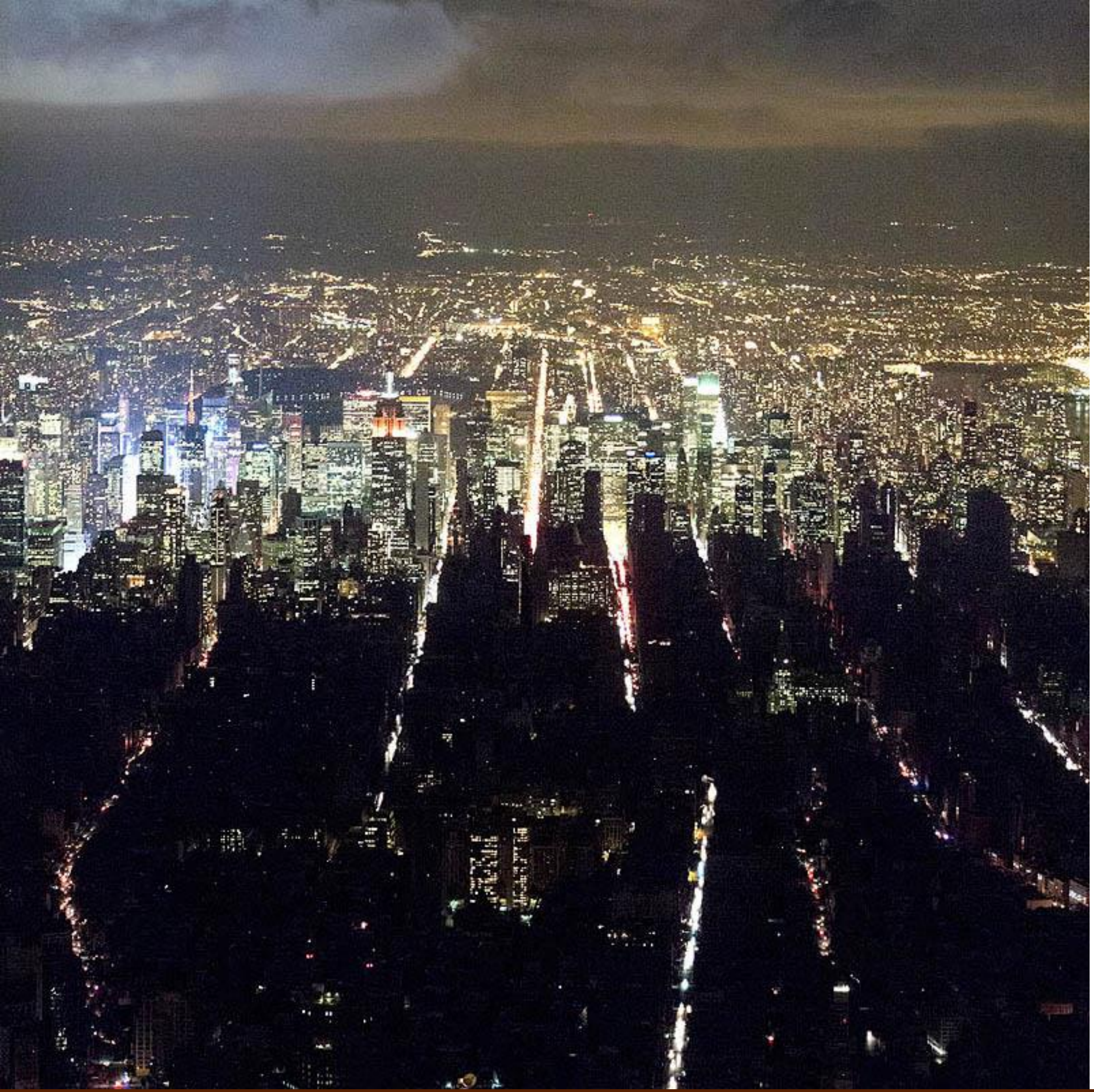




System Recovery







Conclusions

- To understand catastrophes, we need models that are complex enough to capture all the important features, but simple enough to be explainable.
- Finding the right balance of complexity and simplicity through surrogation is a technical challenge, and also an art.
- The proper study of natural disasters is a highly interdisciplinary task, which requires teams of people with different backgrounds.

An Academia – Industry Consortium

CERCat | Consortium for Enhancing Resilience and Catastrophe Modeling

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RICE

Site

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WASHINGTON STATE UNIVERSITY

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CERCat Faculty

- 18 Faculty members
- 2 sites, 6 total institutions
- Spanning many departments, schools, colleges, and areas of science such as:
  - Civil Engineering
  - Statistics
  - Atmospheric Science & Climate Change
  - Urban & Regional Planning
  - Hydrology
  - Remote Sensing & Computer Vision
  - Environmental Engineering
  - Mathematics
  - Structural Engineering
  - Sociology
  - Data Science, ML, AI
  - Water Resources Engineering
  - Public Policy
  - Computer Science
  - Population Health
  - …

CERCat Members

Insurance companies

Software companies

Reinsurance companies

CatModeling firms

Large (engineering) consulting firms

Banks and Mortgage Companies

Large Asset Owners

Climate data companies

Federal agencies and labs

Professional societies

CERCat Value Proposition

Single point of access to top talent and world-class research

- 18 renowned faculty members in core CatModeling disciplines and complementary areas.
- Over 100 bright students per year at the Bachelor, Master, and Doctoral levels.
- Ability to mentor and train students and create a pipeline.

Ability to steer research topics, early access to research and IP

- High return on investments with jointly funded projects.
- University contributions lower overhead.

Professional networking opportunities in the private sector, public sector, and academia

- Ecosystem of companies in complementary fields.
- Recurring events to engage with collaborators, clients, vendors, regulators, etc.
- Opportunities for continuous education, professional development, and initial personnel training

CERCAT

Bocchini Research Group @ Lehigh

Main topics
- Computational simulation
- Probabilistic modeling applied to civil engineering
- Infrastructure and community resilience
- Catastrophe modeling

Members (13 scholars)
- 1 Research Scientist
- 1 Postdocs
- 6 PhD students
- 2 Master student
- 2 undergraduates

… and 1 advisor

Thanks to Our Sponsors

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