Energy Infrastructure Risk models through Hawkes hazard models and Bayesian Vulnerability Networks

- In this work, we identify energy infrastructure to be critical as its failure has a damaging impact on health, safety , security and well being of society.

- We identify hazards as random events that has a causal relationship with failure of energy infrastructure.

E.g.-

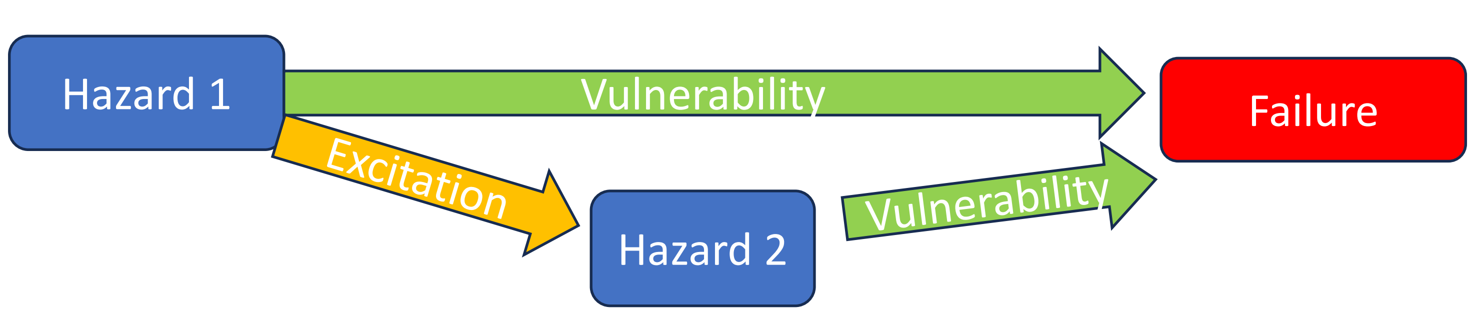
- Severe Weather Events:
  - Hurricanes/Typhoons/Cyclones - lightning
  - Tornadoes
  - Snowstorms/Ice Storms
  - Earthquakes
  - Floods
  - Wildfires
  - Volcanic Eruptions
  - Geomagnetic Storms
  - Tsunamis
  - Droughts
  - Landslides

- Cyberattacks
- Physical Attacks -terrorism
- Technical Failures
- Human Errors
- Fuel Supply Disruptions
- Regulatory and Policy Changes
- Infrastructure Aging
- Supply Chain Disruptions
- Environmental Regulations
- Social and Political Unrest
- Economic down-turns and financial crisis

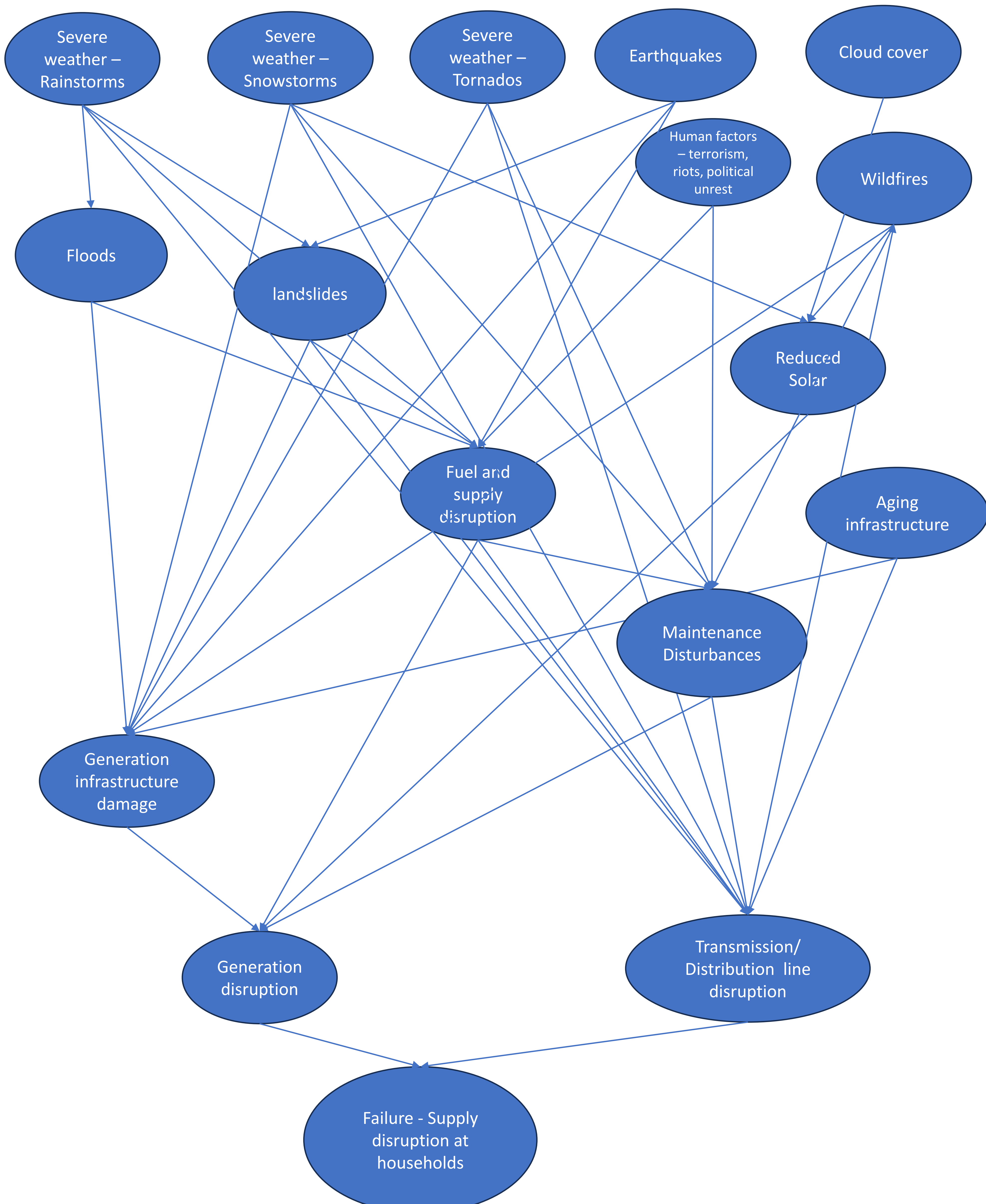
- We observe these hazards has self-excitation – earthquakes increase the probability of happening more earthquakes (aftershocks).

- Some of them has mutual excitation – Rainstorms increases probability of floods occurring, Earthquakes increases probability of landslides occurring.

- Vulnerability represent how each hazard influences failure through exciting further hazards.



- Example graphical structure representing influence through cascading hazards towards failure.



Introduction : Modelling Hazards

- Occurrence of hazards is a random process that can be modelled by a point process.
- Each hazard has features that can be measured in addition to it occurrence .
  (severity of an earthquake, rainfall amount, snowfall inches)
  Therefore, it can be represented by a marked point process (Li, 2021).
- The intensity of this point process must capture the self excitation and mutual excitation properties. The intensity represent the infinitesimal probability of occurrence of a hazard.
- We propose to use Hawkes point processes (Hawkes, 1971) to capture this dynamic intensities.
- A self excited marked Hawkes process $N(t)$ of type $k \in K$, $t \in \tau$ can be described with intensity function as follows.

$$\lambda(t,k) = \mu + \int_0^t \gamma(t-u,k)dN(u)$$

  Here μ is the Poisson base intensity and $\gamma: \tau \times K \to \mathbb{R}$ is called the kernel function that represent the self excitation.
  This can be an exponentially decaying terms to represent decaying excitation.

- Then we state the marked hawks process including cross excitation terms to represent the mutual excitation of each hazards. We denote the intensity of i^{th} hazard process $N_i(t)$ as follows. $i = 0, \dots, D$.

$$\lambda_i(t,k) = \mu_i + \sum_{j=0}^{D} \int_0^t \gamma_{ij}(t-u,k)dN_j(u)$$

here, γ_{ij} denotes the kernel function that represent the excitation of process N_i by a process N_j.

- Now, we see that each hazard process has self and mutual excitation terms that influence intensity of occurrence of a hazard.
- Each excitation can be visualized as an edge in a directed graph where the nodes represent the hazard processes.

Introduction : Modelling Vulnerability

- We propose to use Bayesian networks to model the vulnerability to hazard occurrences and influence flow through it towards failure.
- Bayesian networks have been used in literature for modeling vulnerabilities that exist in a variety of areas.
- (Zhang,2020) uses Bayesian networks to model huma vulnerability in earthquakes and landslides, while work in (Gallardo, 2022) models poverty vulnerability suing Bayesian networks.
- In (Li,2010) insurance vulnerability has been modeled using Bayesian networks.
- Bayesian networks have been applied for vulnerability models related to cyber security as well. (Abaramov,2016)
- Proposed Vulnerability metric can be evaluated through conditional probability of a failure given the hazard intensities.
- Example: for a failure intensity f_j given hazard intensities λ_h^i for $i = 1, .., n$,

$$Vulnerability = P(f_i | \lambda_h^1, \dots, \lambda_h^n)$$

  This evaluates the exposure of the infrastructure to the i^{th} hazard.
- For each type of failure, the influence of hazards flow through the vulnerability triggering further hazards. The proposed model captures this influence flow.

Problem Statement

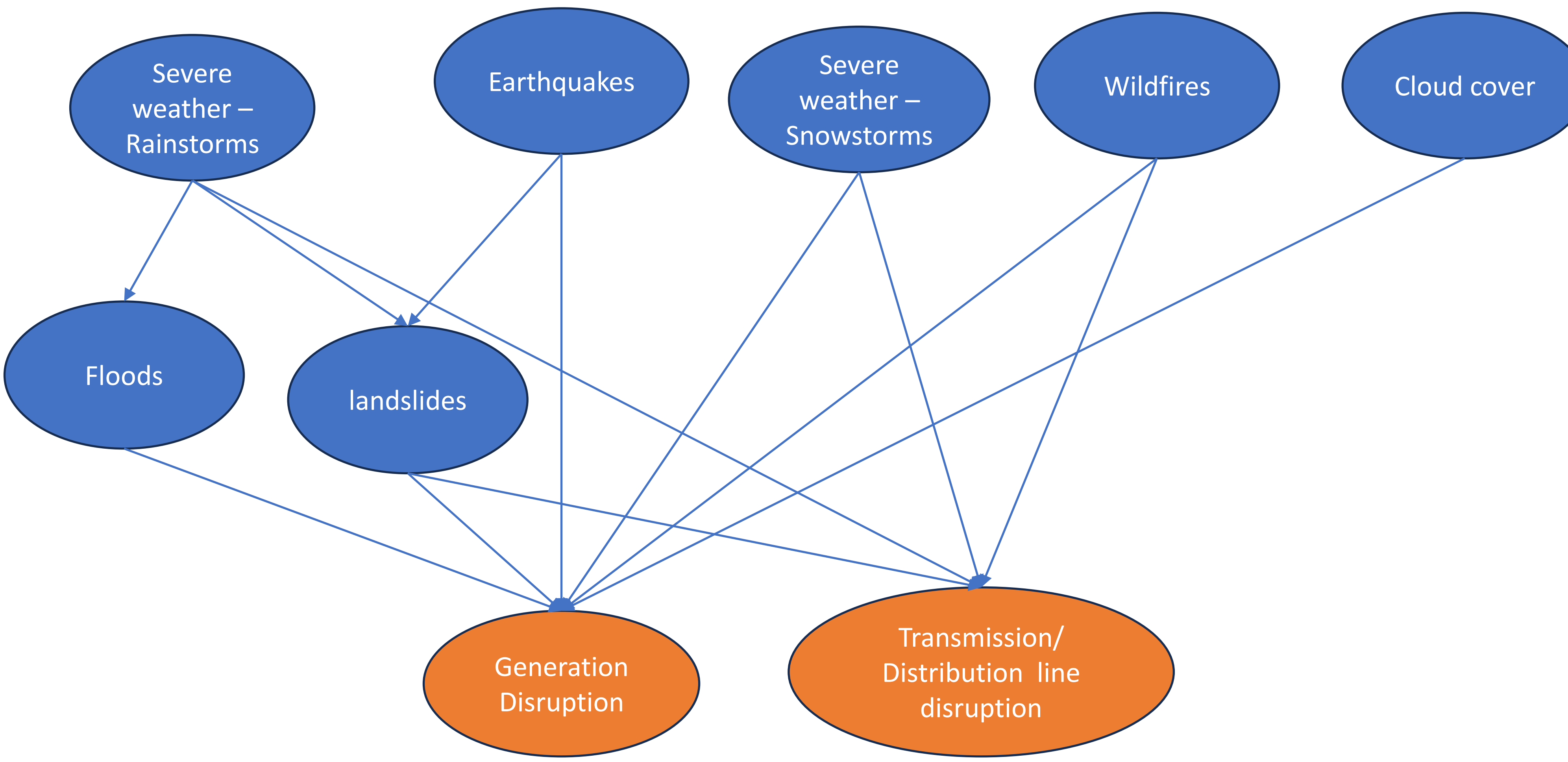
- For a selected geographical area, our goal is to identify the hazards and vulnerabilities to the energy infrastructure in that region. To this end, we select the north-east region of the United States.
- For the northeast region, we narrow down the possible hazard follows.
  Rainstorms Snowstorms Earthquakes Wildfires Cloud cover Floods Landslides
- Any of the above hazard has an influence in triggering, generation disruptions and transmission disruptions, which causes failure.
- The problem is to:
  - Estimate the model parameters of the intensity process that describes the hazard occurrence.
  - Learn the structure of the Bayesian network that represents influence flow from statistical methods.
  - Prune/ enhance the structure using domain knowledge.
  - Estimate parameters of the Bayesian network to learn the condition probability distribution that describes the vulnerability metrics.

Estimating the hazard model

- Learning the hazard model, involves modeling the hazards and their cross excitations by a set of Hawkes intensity processes.
- It requires data on recorded hazard occurrences for estimating the hawkes process kernels and their cross-excitation coefficients.

Estimating the Vulnerability model

- We start with statically learning the structure of the vulnerability network.
- However, statistical structure learning methods usually yield highly complex structures, (Song,2012)
- Therefore, we employ domain knowledge to do pruning and adjustments to the network.
- An example vulnerability network for northeast would be as follows.



- With the network structure fixed, we can then learn the parameters of the conditional probability distributions to do inference using the graph.

Required Data

- Precipitation Data- Rainstorms-Snowstorms – NASA POWER
- Cloud- Cover – NASA POWER

- Earthquake Data
- Wildfire Data
- Floods
- Landslides

- Energy Infrastructure data
    - Generation types- locations
    - Critical Transmission arterials- graph
- Historical record of disruptions

Baselines

- Parametric regression models
- Decision trees
- ????

References

- Li, X., Genest, C., & Jalbert, J. (2021). A self-exciting marked point process model for drought analysis. *Environmetrics*, 32(8), e2697. https://doi.org/10.1002/env.2697
- Alan G. Hawkes, Spectra of some self-exciting and mutually exciting point processes, Biometrika, Volume 58, Issue 1, April 1971, Pages 83–90, https://doi.org/10.1093/biomet/58.1.83
- Embrechts, P., Kirchner, M. (2018). Hawkes graphs. Theory of Probability & Its Applications, 62(1), 132–156. https://doi.org/10.1137/s0040585x97t988538
- Song, Wenting, et al. "Bayesian network structure learning from attribute uncertain data." Web-Age Information Management: 13th International Conference, WAIM 2012, Harbin, China, August 18-20, 2012. Proceedings 13. Springer Berlin Heidelberg, 2012.