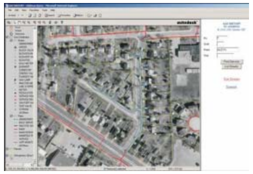
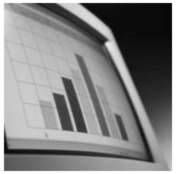
Rapid Stochastic Assessment of Post-hazard Connectivity and Flow Capacity of Lifeline Networks



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Needs for Rapid Stochastic Assessment and Challenges

Stochastic assessment in DSS

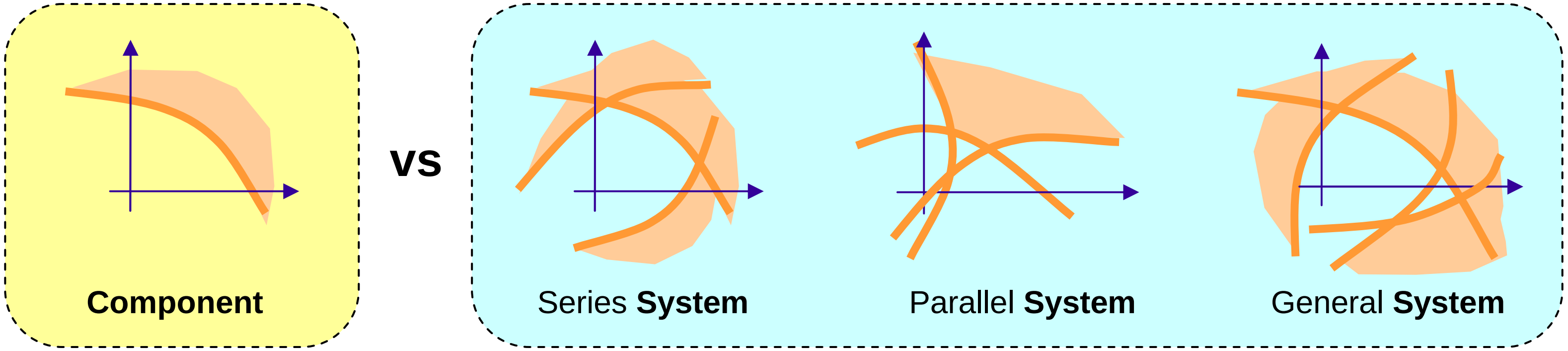
- **Needs for efficient stochastic assessment for lifeline networks**
  - Hazard **mitigation** planning (long-term)
    - can have many scenarios or cases
    - time-variant analysis (deterioration, aging, etc.)
  - Quick hazard **responses** (short-term)
    - proximity of damaged components through probabilistic inference
    - immediate responses to minimize socio-economic losses
  - **Integration** with optimization, information technology, monitoring system

- **Computational challenges**
  - **Complexity** of lifeline networks (size, system effect, etc.)
  - **Spatial correlation** of hazard intensities (further increase the system size)
  - **Importance** measures (component, uncertainty, etc.)
  - Parameter **sensitivities**
  - **Integration** with network flow (capacity and/or demand) analysis
  - **Time-variant** analysis (deterioration)

It's system reliability problem!

* Song, J. and A. Der Kiureghian (2003). Bounds on system reliability by linear programming, *Journal of Engineering Mechanics*, 129(**6**), 627-636.

- ## System reliability analysis (SRA)
  - System event E_{sys}: logical function of component events, E_i, $i = 1, \ldots, n$

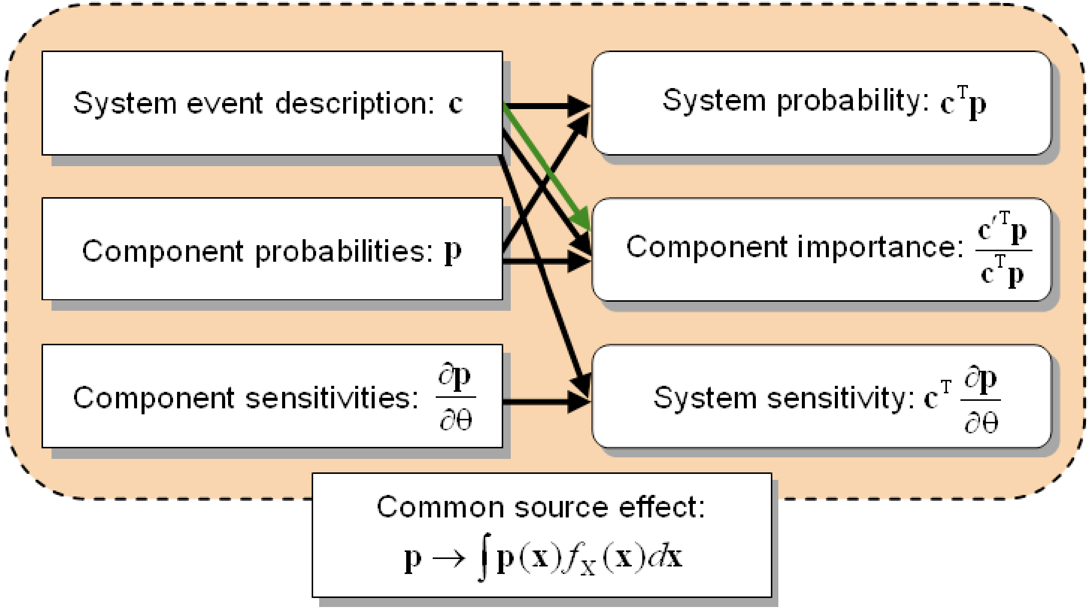


  - $P(E_{sys})$: theoretical bounding formulas (Ditlevsen), sampling methods, and direct integration in random variable space

- ## Challenges in SRA
  - **Complexity** of system reliability problems: large number of components, difficulty in identifying critical cut sets or link sets, computational challenges
  - **Statistical dependence** between component states (common source effect)
  - **Diversity or lack** of available **information**
  - Difficult to **identify important components or parameters** (critical for decision support)

Matrix-based System Reliability (MSR) method

* Song, J. and W.-H. Kang (2009). System reliability and sensitivity under statistical dependence by matrix-based system reliability method, *Structural Safety*, 31(**2**), 148-156.

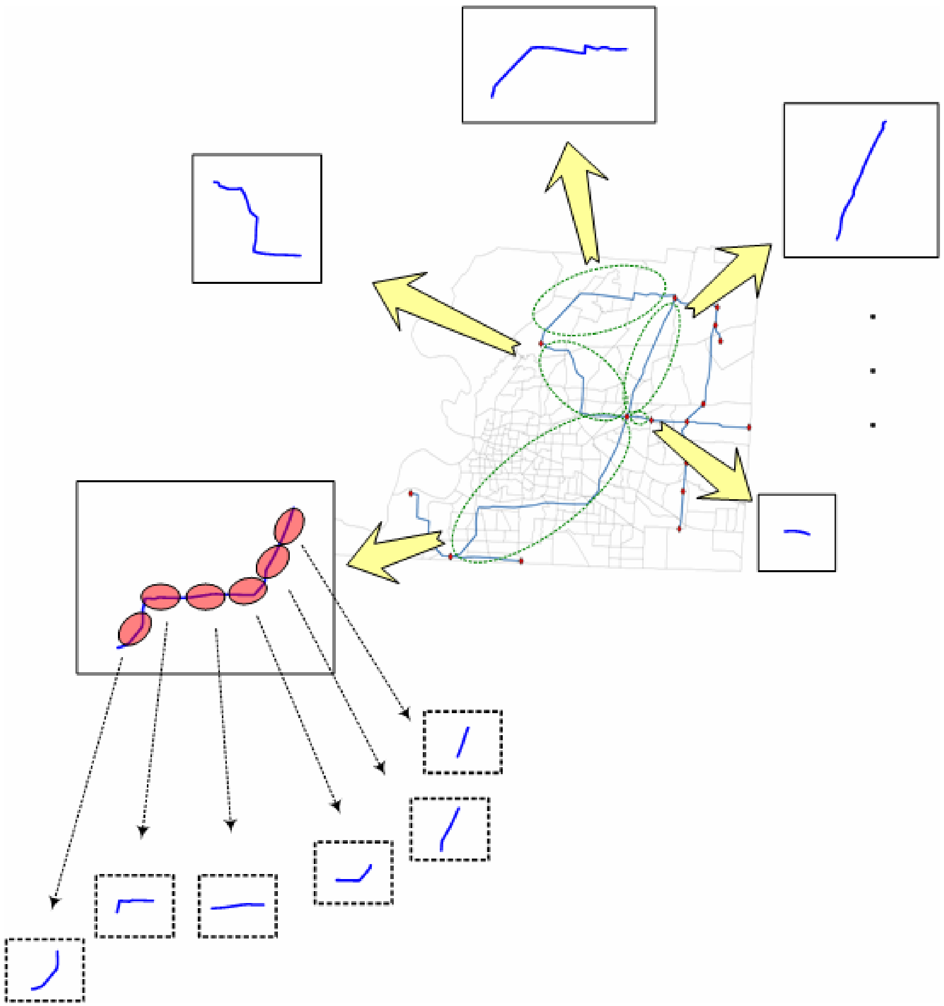


- **Convenient**: matrix-based procedures for **c** and **p**; easy SRA calculation (inner product)
- **General**: uniform application to series, parallel, and any general systems
- **Flexible**: inequality-type information; incomplete information ("LP bounds" method)
- **Efficient**: no need to re-compute "**p**"; replace "**c**" for SRA of a new event
- **Common Source Effect**: can account for statistical dependence between components
- **Decision Support**: parameter sensitivities, component importance measure; inferences

App1: Post-hazard connectivity of gas pipeline network

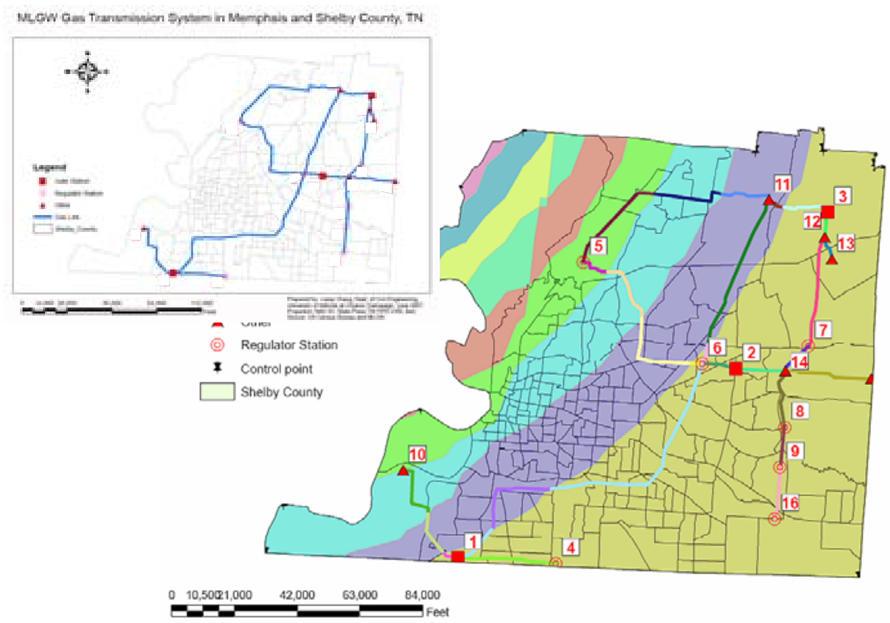
Multi-scale SRA of lifeline networks

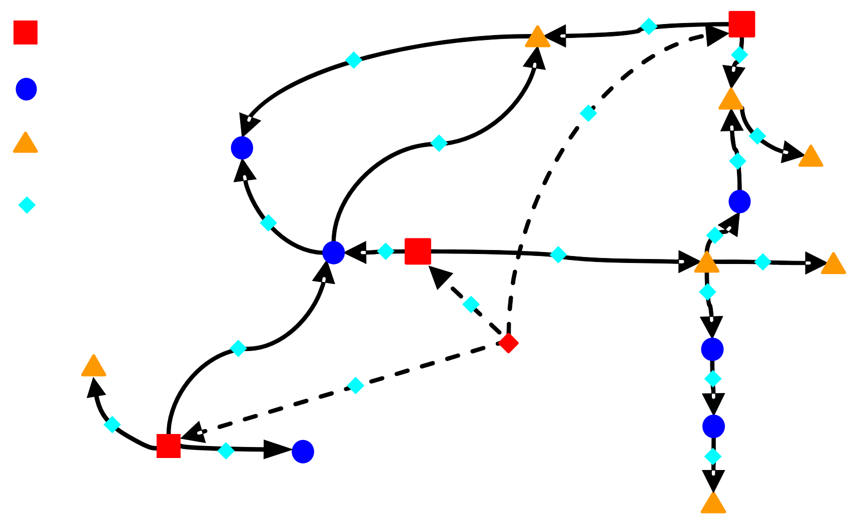
* Song, J., S.-Y. Ok, and L.. Chang (2008). Rapid risk assessment and decision support for urban infrastructure networks by MSR method. *Proc. Inaugural International Conference of the Engineering Mechanics Institute*, May 18~21, Minneapolis, MN.



- **"Divide and Conquer" approach**
  - Lower-scale system reliability analyses are performed for "supercomponents" and followed by higher-scale system reliability analyses
  - Proposed to facilitate the use of **LP bounds method** (Song and Der Kiureghian, 2003) for large-size systems
  - **MSR method** is a good tool for SRA at multiple scales
- **Advantages**
  - **Multi-scale modeling** of a system – seeing big picture without disregarding the details
  - Helps identify **important** components and parameters at **multiple scales**
  - **Collaborative** risk management
  - Facilitates parallel computing

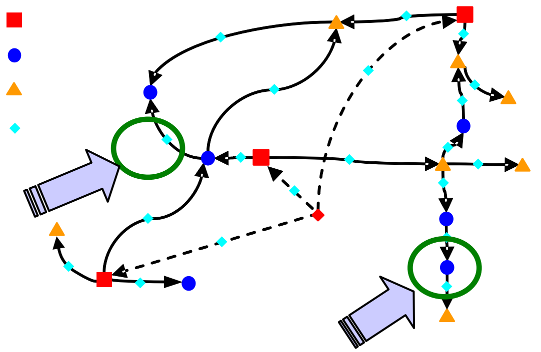
Example: MLGW gas network





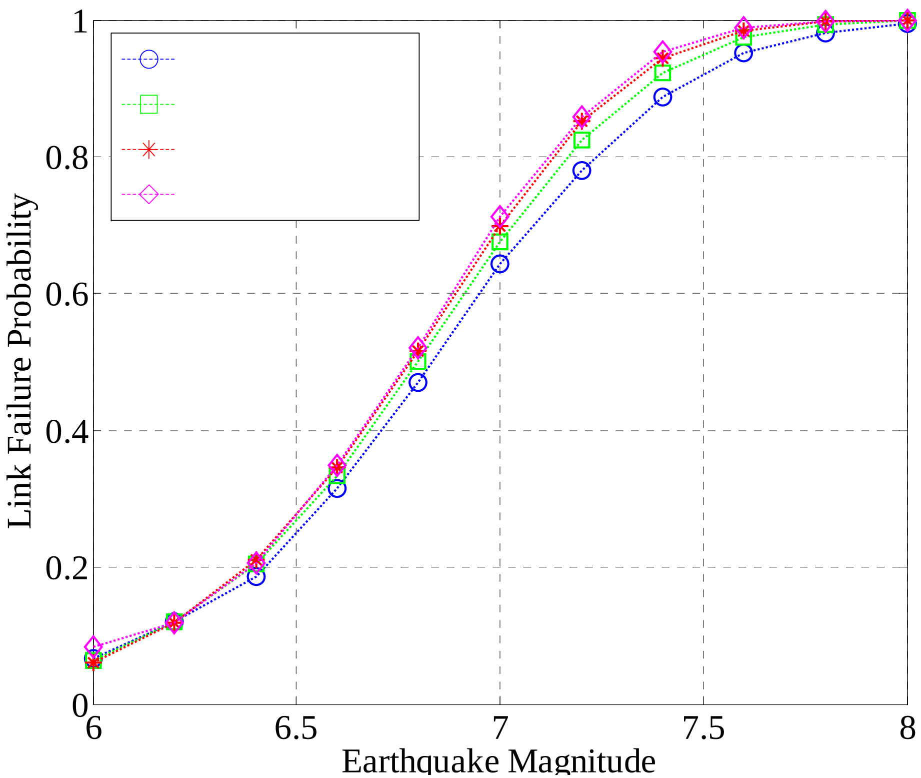
- Gas pipeline network of Memphis Light, Gas, and Water (MLGW), Shelby County, TN
- A simplified network in Chang et al. (1996) was modified based on comments from R. Bowker (MLGW)
- 37-node and 40-arc network: nodes representing pipelines and stations
- Earthquake hazard scenarios: Epicenter at N35.54º-W90.43º at Blytheville, AR
- Fragilities of pipelines and stations – *HAZUS-MH*
- PGV and PGA maps from *MAEviz*

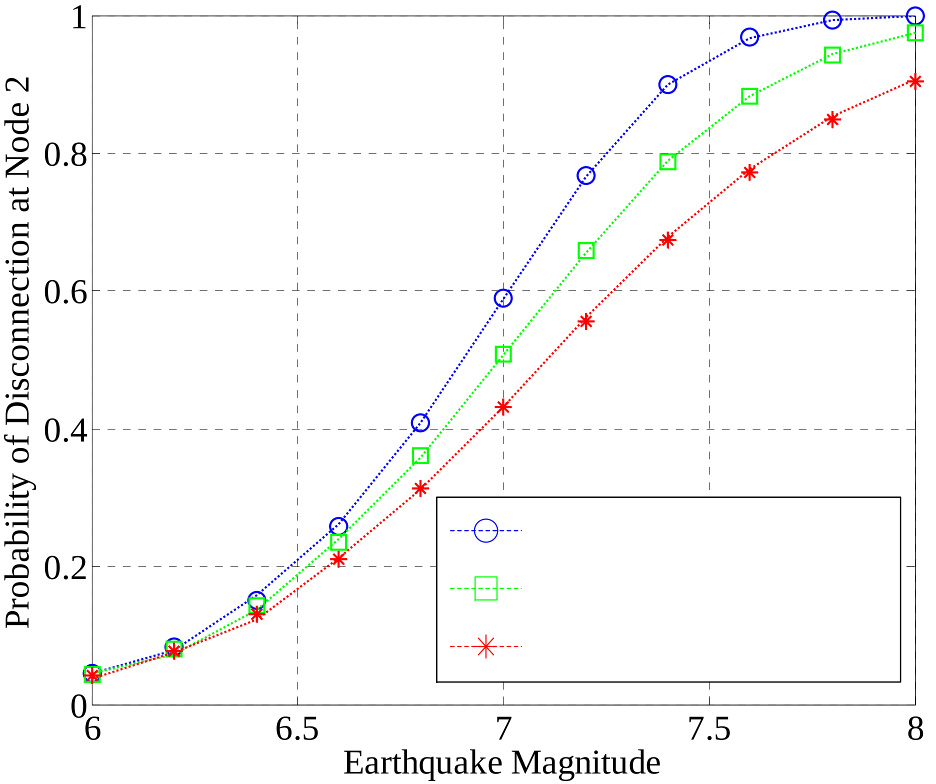
Risk at multiple scales



Lower-scale: pipelines

Failure probability of **Link** 25



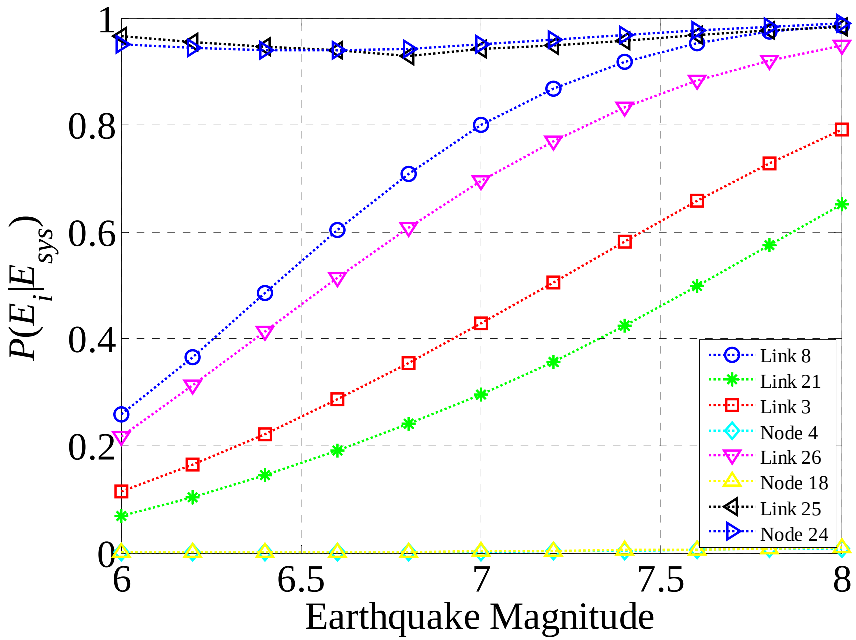


Higher-scale: service nodes

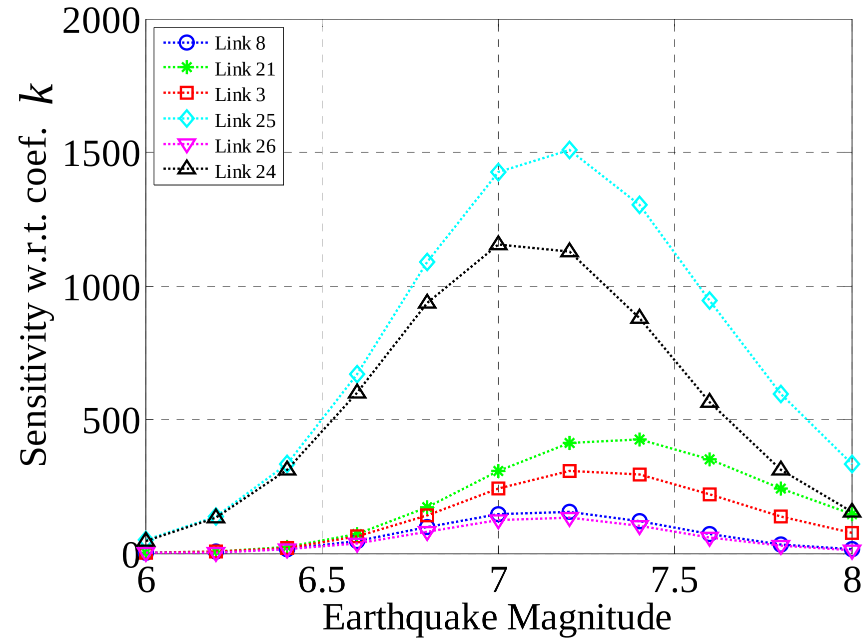
Prob. of Disconnection at **Node** 2

Probabilistic inference and sensitivity

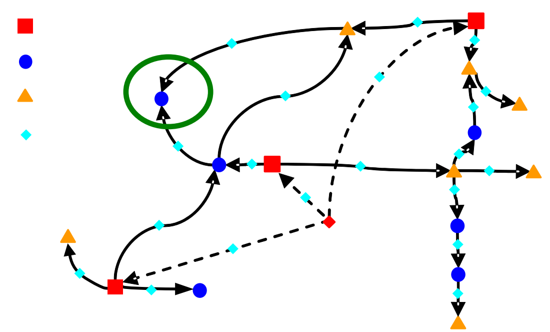
Conditional Probabilities



Parameter Sensitivity



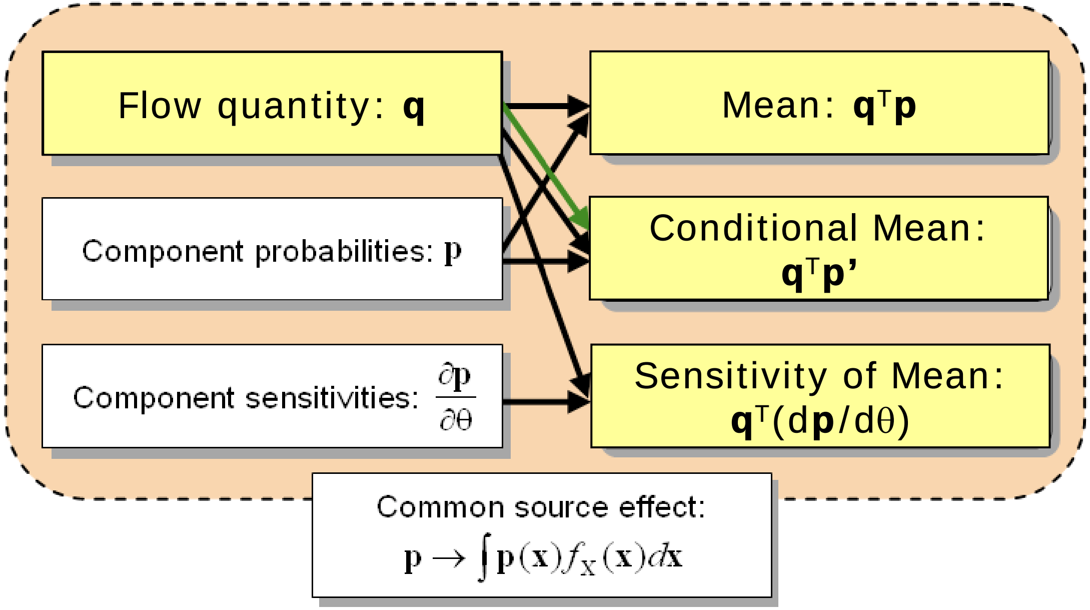
- Conditional probability of link failure probability given observed system event (e.g. disconnection)
- Sensitivity of system failure probability with respect to parameters in PGV-based model for failure occurrence rate: $\nu_i = k \cdot (PGV_i)^{\gamma}$



App2: Post-hazard flow capacity of bridge transportation network

Extension for network "flow" analysis

* Lee, Y.-J., J. Song, and P. Gardoni (2009). Post-hazard flow capacity of bridge transportation network considering structural deterioration, *ICOSSAR2009* (will be presented), Osaka, Japan.

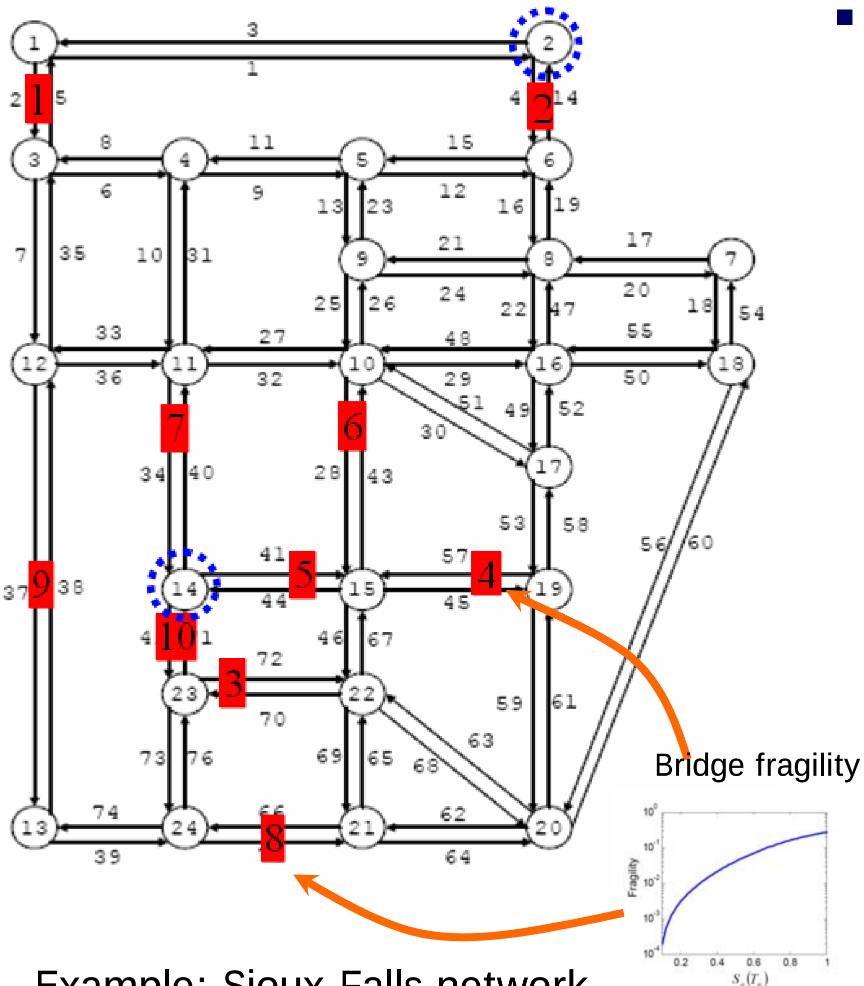


- **Multi-state failures**: can handle more than two failure/damage states

- **Separation between network flow analysis and vulnerability analysis**:

1) No need to repeat network flow analysis (**q**) for time-varying fragility (deterioration, etc.)
2) No need to repeat probability calculations (**p**) for changes in network (new routes, etc.)
3) Flow analysis for damage scenarios with high likelihood only (for approximation)

Post-hazard flow capacity of a bridge network



Example: Sioux-Falls network

Red: bridges; **Circles**: Starting & Ending points

- Traffic flow **capacity** between two points in a network → determined by combinations of bridge damages

  $\mathbf{q}$: a vector of network flow capacity for bridge failure combinations (obtained by maximum flow capacity analysis)

$$\mu_Q = \mathbf{q}^T \mathbf{p}$$

: average post-hazard flow capacity

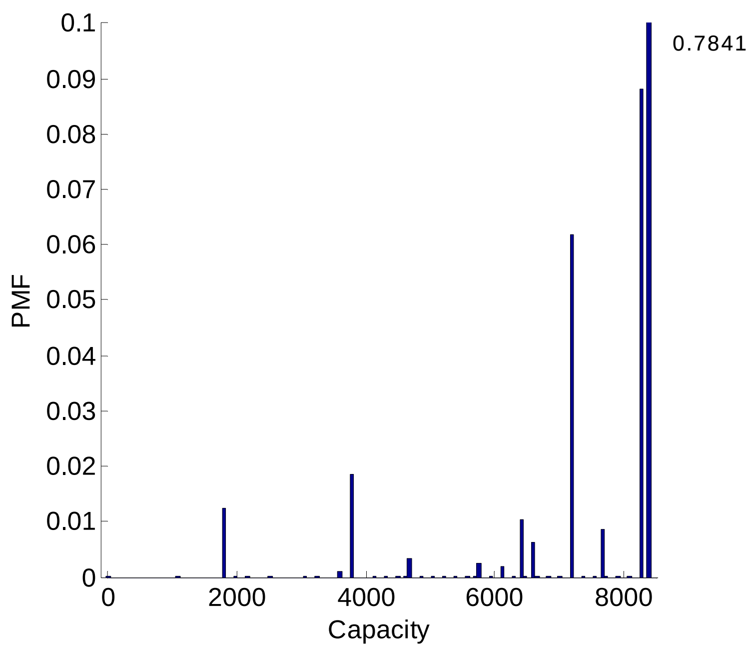
$$\sigma_Q^2 = (\mathbf{q}.*\mathbf{q})^T \mathbf{p} - (\mathbf{q}^T \mathbf{p})^2$$

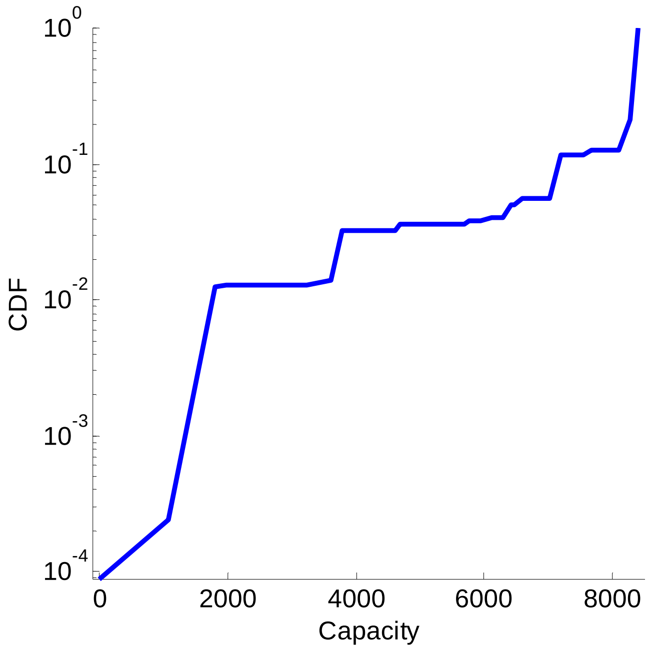
: variance of post-hazard flow capacity

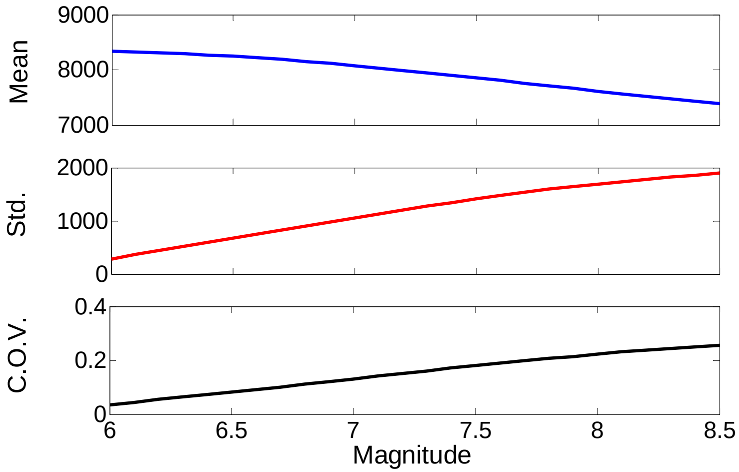
$$P(Q < a) = \sum_{\forall i: q_i < a} p_i$$

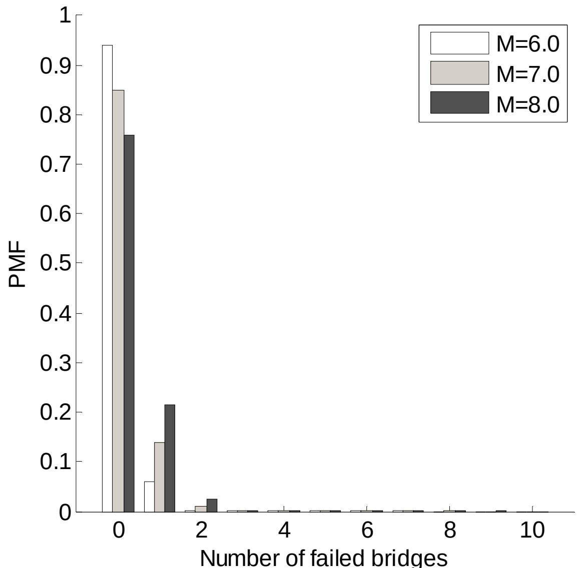
: probability that flow capacity is lower than *a*

Uncertainty quantification of flow capacity



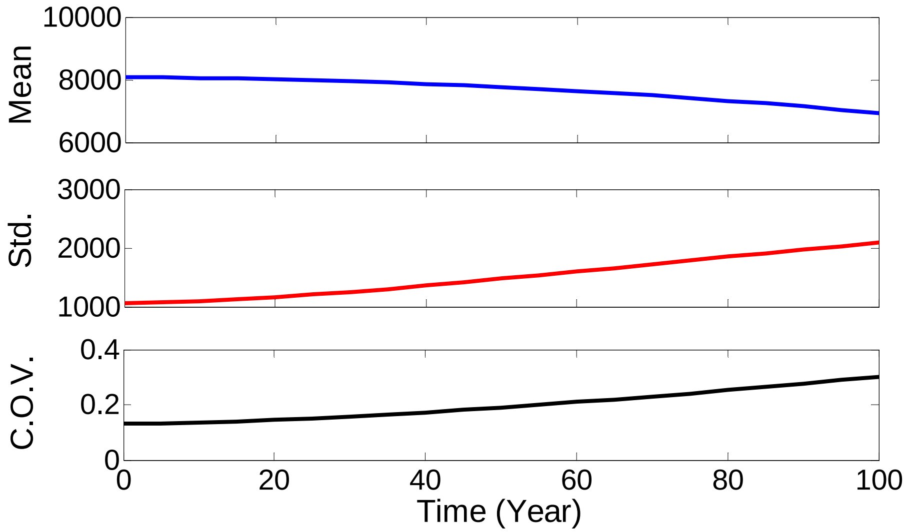






Time-variant analysis; Reduction factor

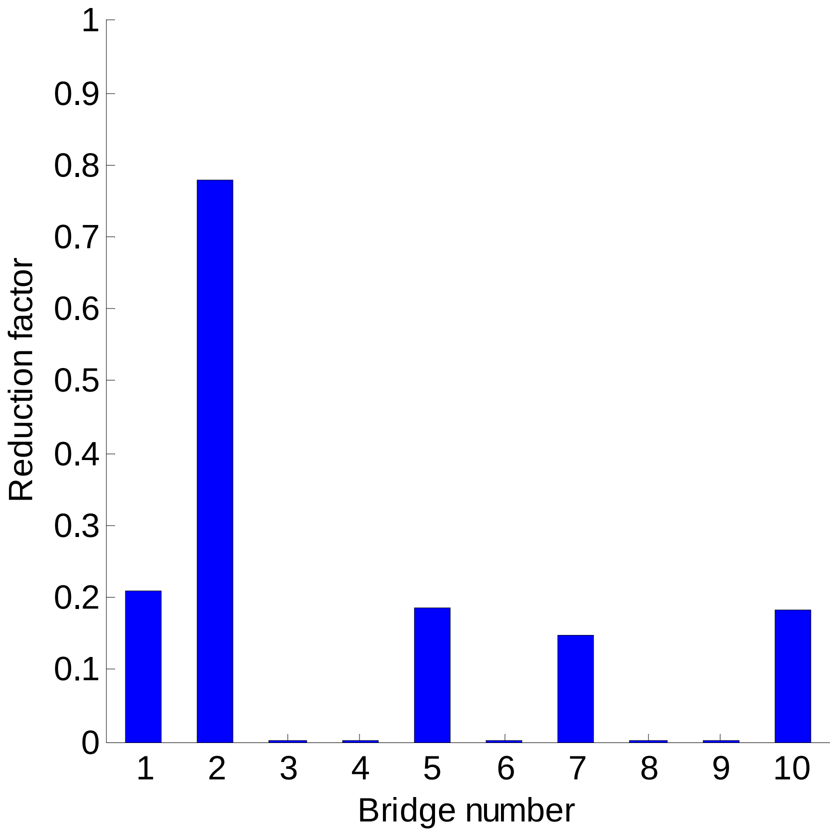
Time-variant mean, std., and c.o.v. of flow capacity



$$\mu_Q(t) = \mathbf{q}^{\mathrm{T}}\mathbf{p}(t)$$

$$\sigma_Q(t) = \sqrt{(\mathbf{q}.*\mathbf{q})^{\mathrm{T}}\mathbf{p}(t) - \mu_Q^2(t)}$$

Reduction of mean flow capacity by the failure of a bridge



$$RF = 1 - \frac{\mu_{Q|\text{bridge failure}}}{\mu_Q}$$

Summary

- ## Research needs and recent developments
  - **Multi-scale system reliability analysis**:
    - Spatial correlation of seismic intensity
    - Large size network
    - Control modeling efforts at multiple scales
    - Component importance measures
    - Parameter sensitivities
  - **Separation** between **network flow analysis** and **vulnerability analysis**:
    - Flexible uncertainty quantification of network flow metrics
    - Efficient network flow analysis due to separation
    - Importance measures w.r.t. network flow

- ## Ongoing/future research
  - **Online integration** with information technology including monitoring system
  - **Near-real-time probabilistic inference** through machine learning algorithms

Thank you!