Frontiers in Energy Research

Resilience of Electric Power Supply Systems

Max Didier

Contributors:

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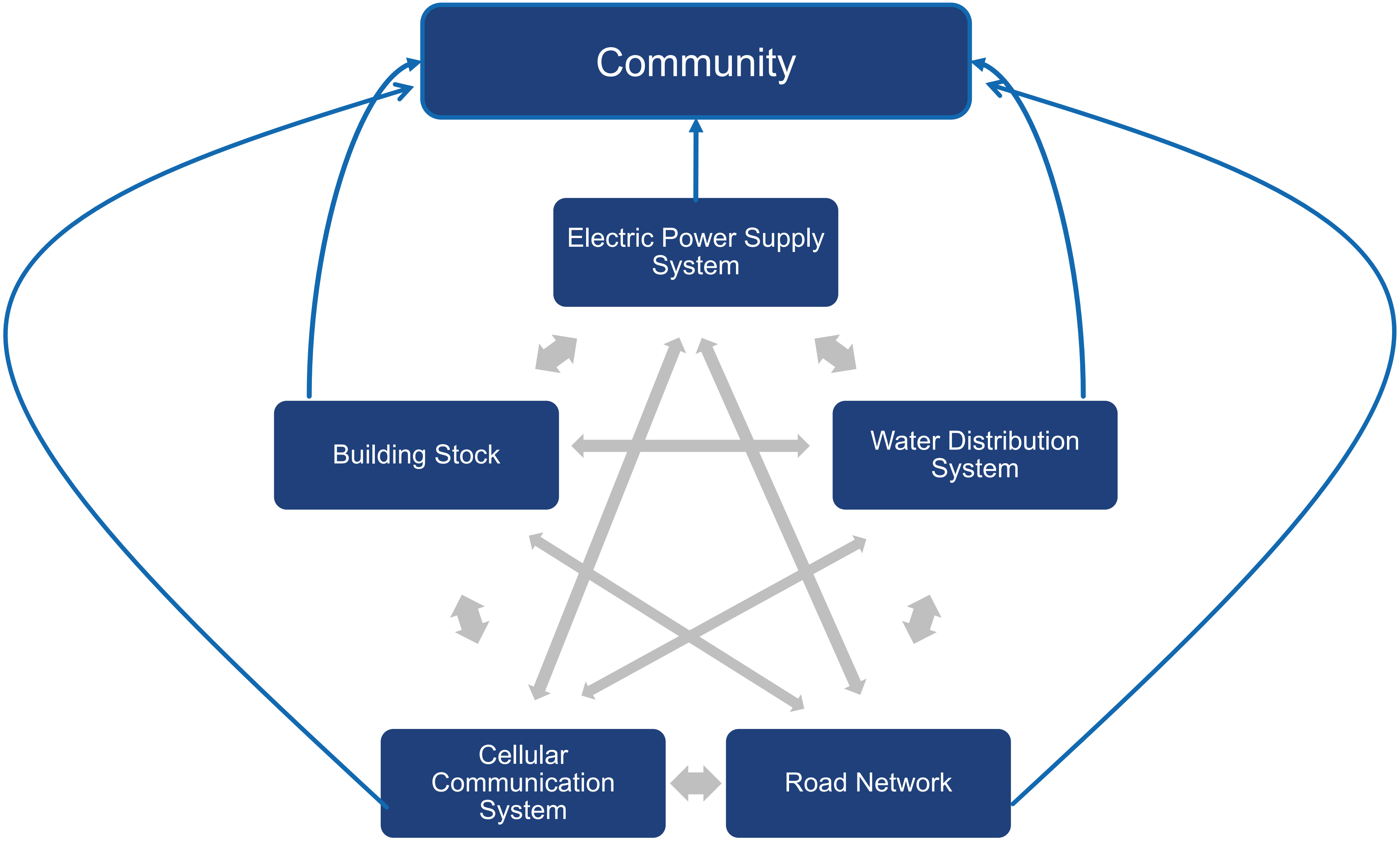
Electric Power Systems and Earthquakes

Significant damage caused to electric power supply system after past earthquakes, e.g.:

- 1994 Northridge (USA) earthquake
- 2011 Tohoku (Japan) earthquake and tsunami
- 2015 Gorkha (Nepal) earthquake

System of Systems - Socio-Technical System



Community

Electric Power Supply System

Building Stock

Water Distribution System

Cellular Communication System

Road Network

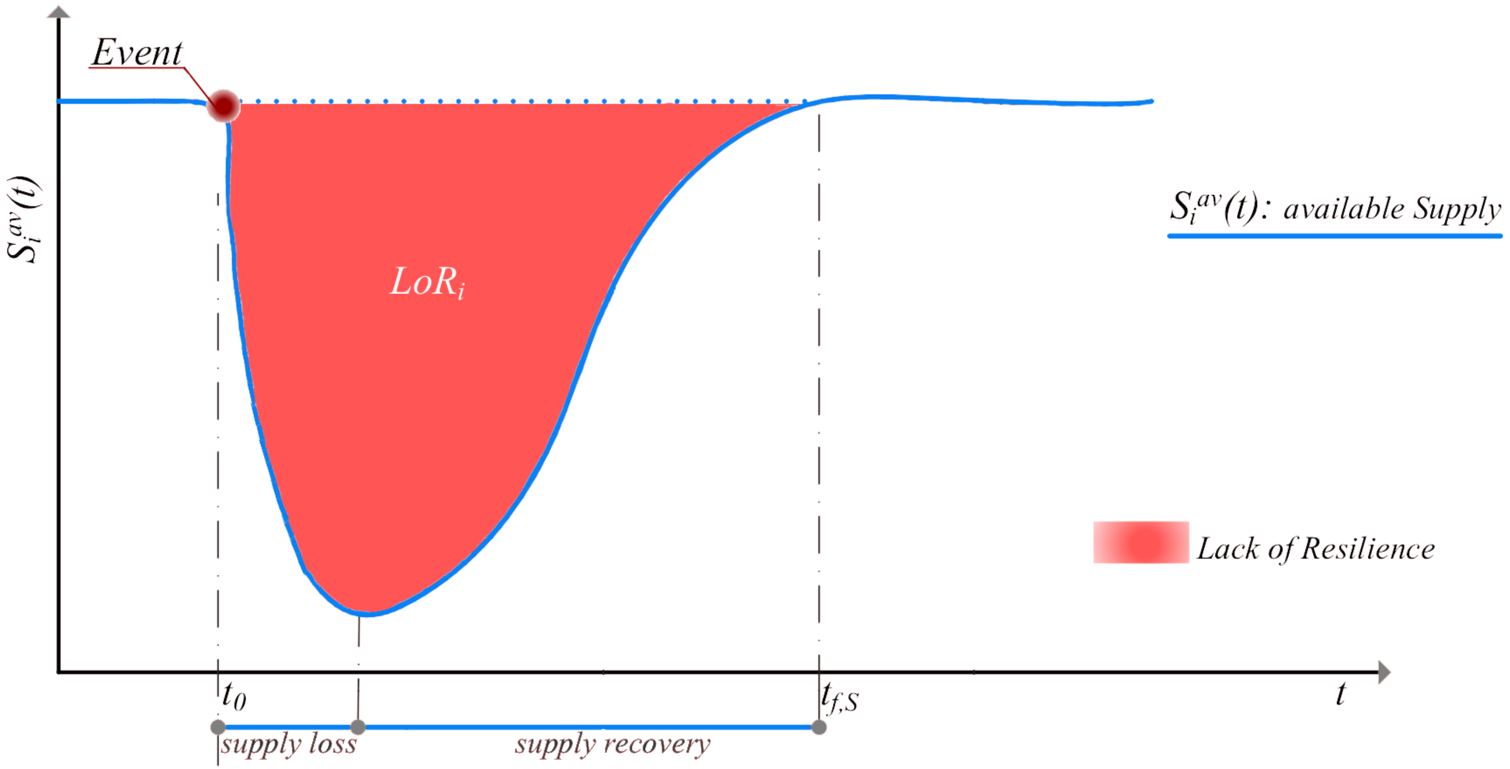
Adapted from Bruneau et al. 2003, A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities

Resilience of Systems

Resilience of civil infrastructure systems can be defined as the time-varying ability of the systems to anticipate, absorb, adapt to, and/or recover from potentially disruptive events that may occur over their lifetime, either back to their original state or an adjusted state based on new requirements.

Combination of the definitions of NIAC (2009) and McCarthy (2007)

Quantifying Resilience



Adapted from Bruneau et al. 2003, A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities

Demand/Supply Interaction

Electric Power Supply System

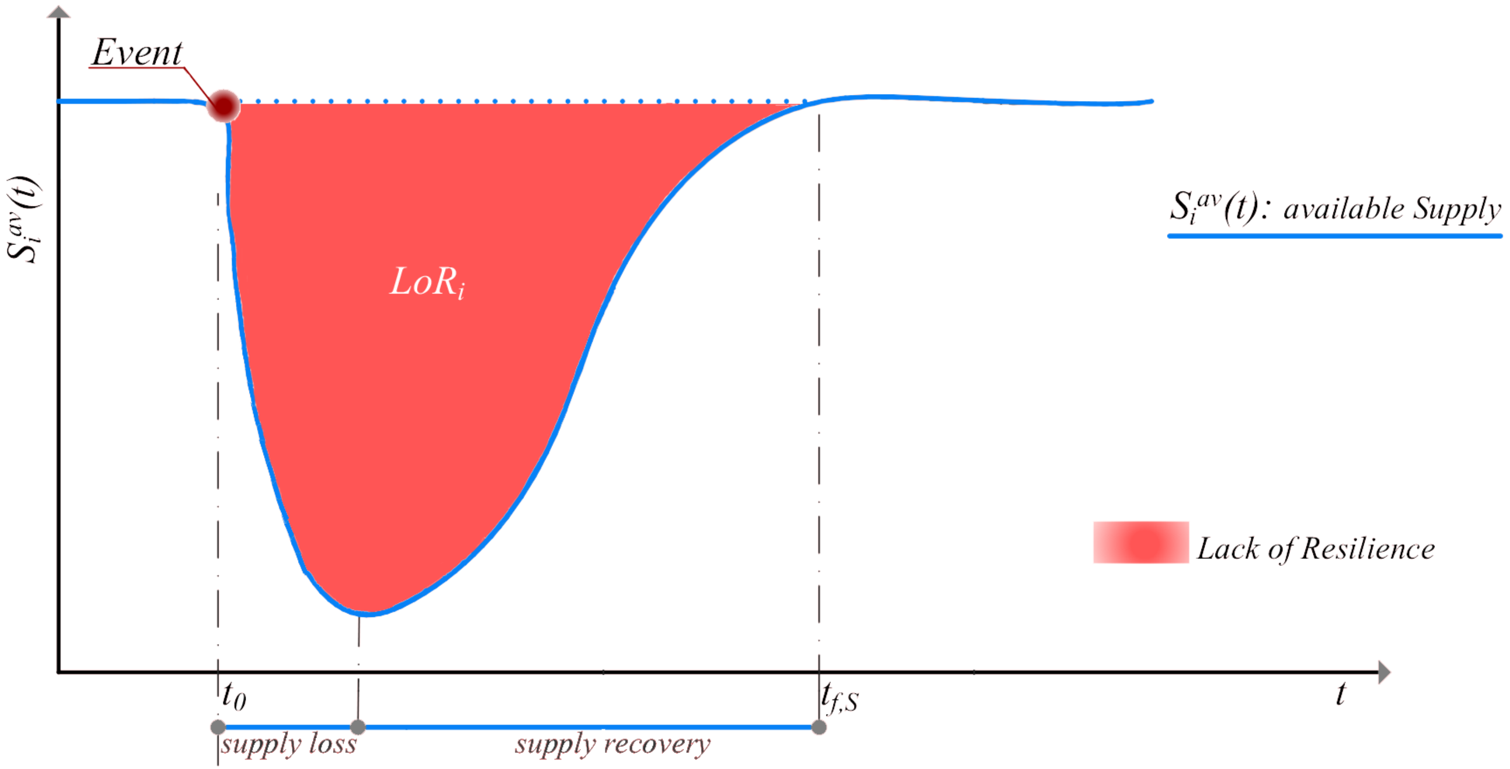
Source: http://www.teara.govt.nz/files/p4537atl.jpg

Community

Source: http://www.japansociety.org.uk/wp-content/uploads/2011/03/191102_182750075103717_182740125104712_433276_3988833_o1.jpg

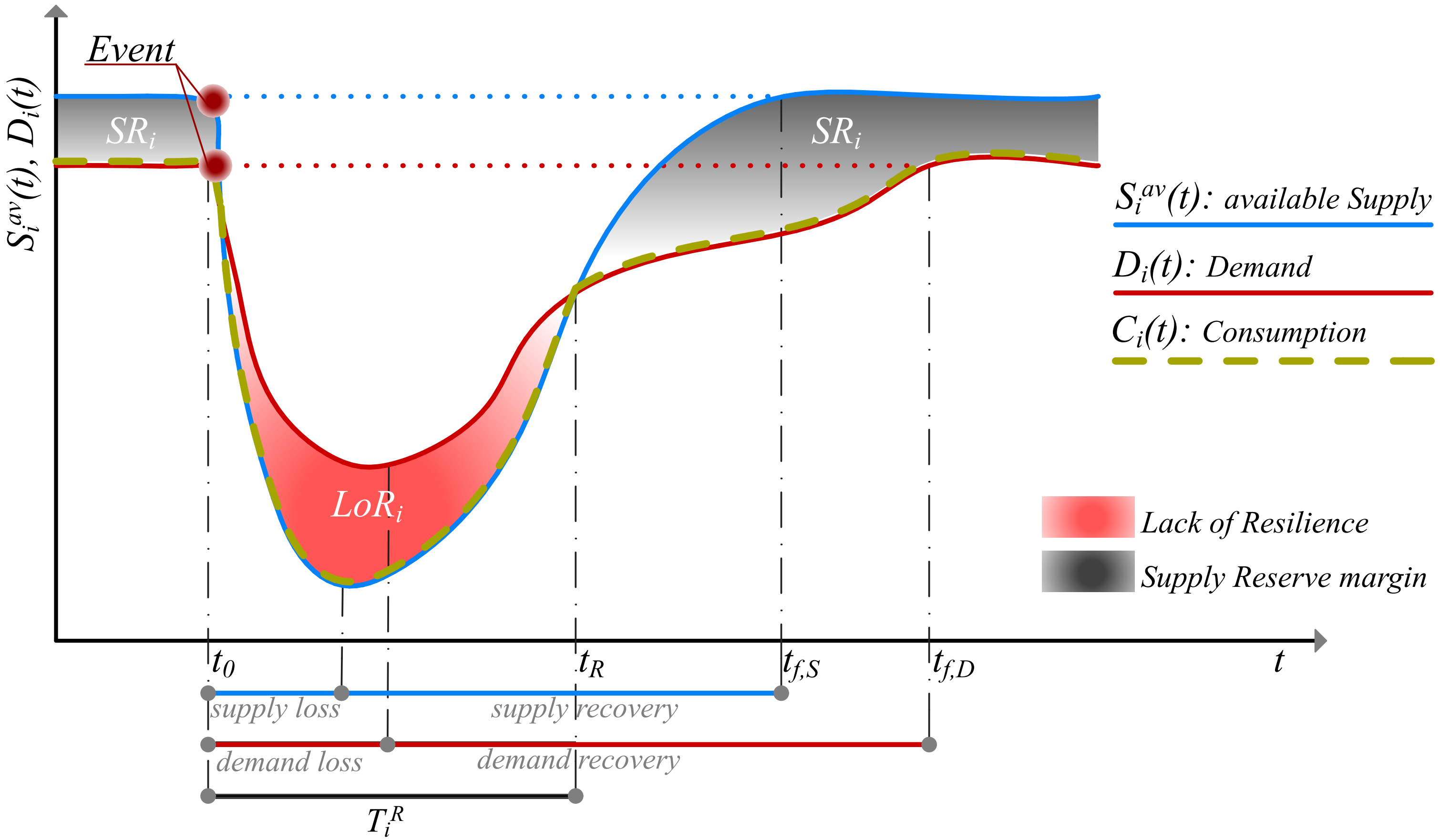
Re-CoDeS framework (Resilience – compositional demand/supply)

Lack of Resilience at the component level



Re-CoDeS framework (Resilience – compositional demand/supply)

Lack of Resilience at the component level



Didier M, Broccardo M, Esposito S, Stojadinovic B (2017). A Compositional Demand/Supply Framework to quantify the Resilience of Civil Infrastructure Systems (Re-CoDeS). *Sustainable and Resilient Infrastructure.*

Re-CoDeS framework (Resilience – compositional demand/supply)

Components

- The **supply layer**, used to model the evolution of the CIS supply, depending on the **vulnerability**, the **recovery** and the **individual supply** of its components.
- The **demand layer**, used to model the evolution of the CIS demand, depending on the **vulnerability**, the **recovery** and the **individual demand** of its components.
- The **system service model,** regulating the allocation (or dispatch) of the CIS service supply in order to satisfy the demand of the consumers.

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Re-CoDeS framework (Resilience – compositional demand/supply)

Resilience quantification

- Component *Lack of Resilience*:

$$LoR_i = \int_{t_0}^{t_f} \langle D_i(t) - S_i^{av}(t) \rangle dt = \int_{t_0}^{t_f} \big(D_i(t) - C_i(t)\big) dt$$

- System *Lack of Resilience*:

$$LoR_{sys} = \sum_{i=1}^{I} LoR_i = \sum_{i=1}^{I} \int_{t_0}^{t_f} \langle D_i(t) - S_i^{av}(t) \rangle dt$$

$$= \sum_{i=1}^{I} \int_{t_0}^{t_f} (D_i(t) - C_i(t)) dt = \int_{t_0}^{t_f} \big(D_{sys}(t) - C_{sys}(t)\big) dt$$

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Re-CoDeS framework (Resilience – compositional demand/supply)

Resilience quantification

- Normalized Component *Lack of Resilience*:

$$\widehat{LoR}_i = \frac{\int_{t_0}^{t_f} \langle D_i(t) - S_i^{av}(t) \rangle dt}{\int_{t_0}^{t_f} D_i(t) dt} = \frac{\int_{t_0}^{t_f} \big(D_i(t) - C_i(t)\big) dt}{\int_{t_0}^{t_f} D_i(t) dt}$$

- Normalized System *Lack of Resilience*

$$\widehat{LoR}_{sys} = \frac{\sum_{i=1}^{I} LoR_i}{\sum_{i=1}^{I} \int_{t_0}^{t_f} D_i(t) dt} = \frac{\sum_{i=1}^{I} \int_{t_0}^{t_f} \langle D_i(t) - S_i^{av}(t) \rangle dt}{\sum_{i=1}^{I} \int_{t_0}^{t_f} D_i(t) dt} = \frac{\int_{t_0}^{t_f} \Big(D_{sys}(t) - C_{sys}(t)\Big) dt}{\int_{t_0}^{t_f} D_{sys}(t) dt}$$

- Component and system Resilience

$$R_i = 1 - \widehat{LoR}_i, R_{sys} = 1 - \widehat{LoR}_{sys}, and\ 0 \leq R_i/R_{sys} \leq 1$$

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Re-CoDeS framework (Resilience – compositional demand/supply)

Advantages

- Re-CoDeS explicitly accounts for both the vulnerability & recovery of the **service supply** and for the vulnerability & recovery of the **community demand** after a event
- It accounts for switches in the demand (e.g. population movement) and changes in the network topology
- **Normalized** measures allow a direct **comparison** between different systems

Interdependent Civil Infrastructure Systems

The slides on interdependent civil infrastructure systems have been removed from the published version of the slides (since the corresponding paper is not yet published).

A pre-print or working paper can be made available by the author (didierm@ethz.ch)

Didier, M., Broccardo, M., Esposito, S. and Stojadinovic, B. (2018). Seismic Resilience of Interdependent Civil Infrastructure System. 11th US National Conference on Earthquake Engineering. Submitted.

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Application of Re-CoDeS

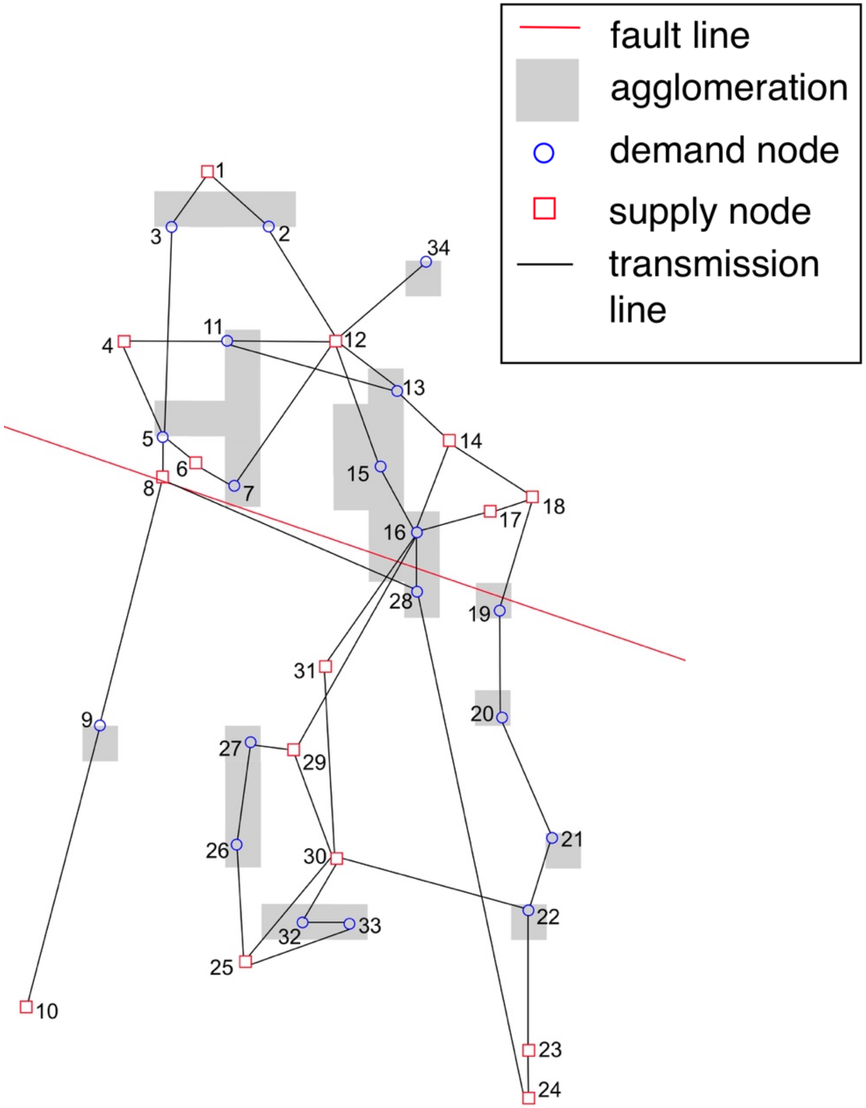
- Application:

  Quantify the resilience of an electric power supply system supplying a virtual community with electric power exposed to seismic hazard.

Application of Re-CoDeS

Study Area

- Part of the IEEE 118 Bus Test Case (representing a portion of the EPSS in the Midwestern US as of December 1962) (Christie 1993)
- 15 supply substations, 19 medium or low voltage distribution substations, 44 transmission links



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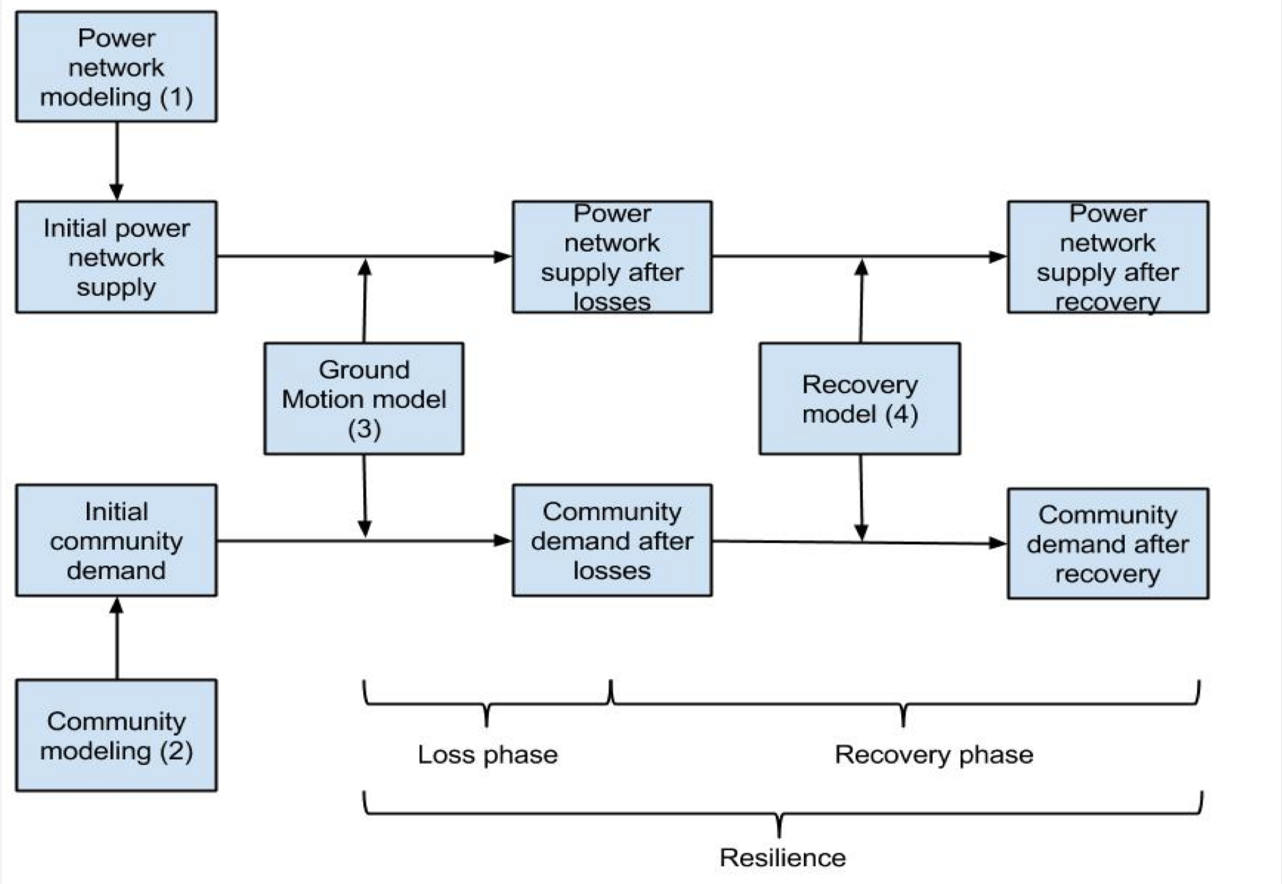
Application of Re-CoDeS

Flow diagram



Application of Re-CoDeS

Seismic Hazard Model

- Study area crossed by a linear strike-slip fault (assumed to extent endlessly outside the map)
- Rupture initiates on a random point of the part of the fault contained in the mapped area (location of epicenter uniformly distributed) and spreads in both directions along the fault
- Magnitude distribution: exponential truncated Gutenberg-Richter (1944) distribution: $M_{min} = 4$, $M_{max} = 7$, $\alpha = 4$, $\beta = 2.4$
- Rupture length: Wells & Coppersmith 1994
- Site-rupture distance: Joyner-Boore 1981
- Ground motion prediction equation (GMPE) of Akkar et al. 2014
- Spatial correlation model for intra-event variability: Esposito & Iervolino 2011
- Stiff soil in entire study

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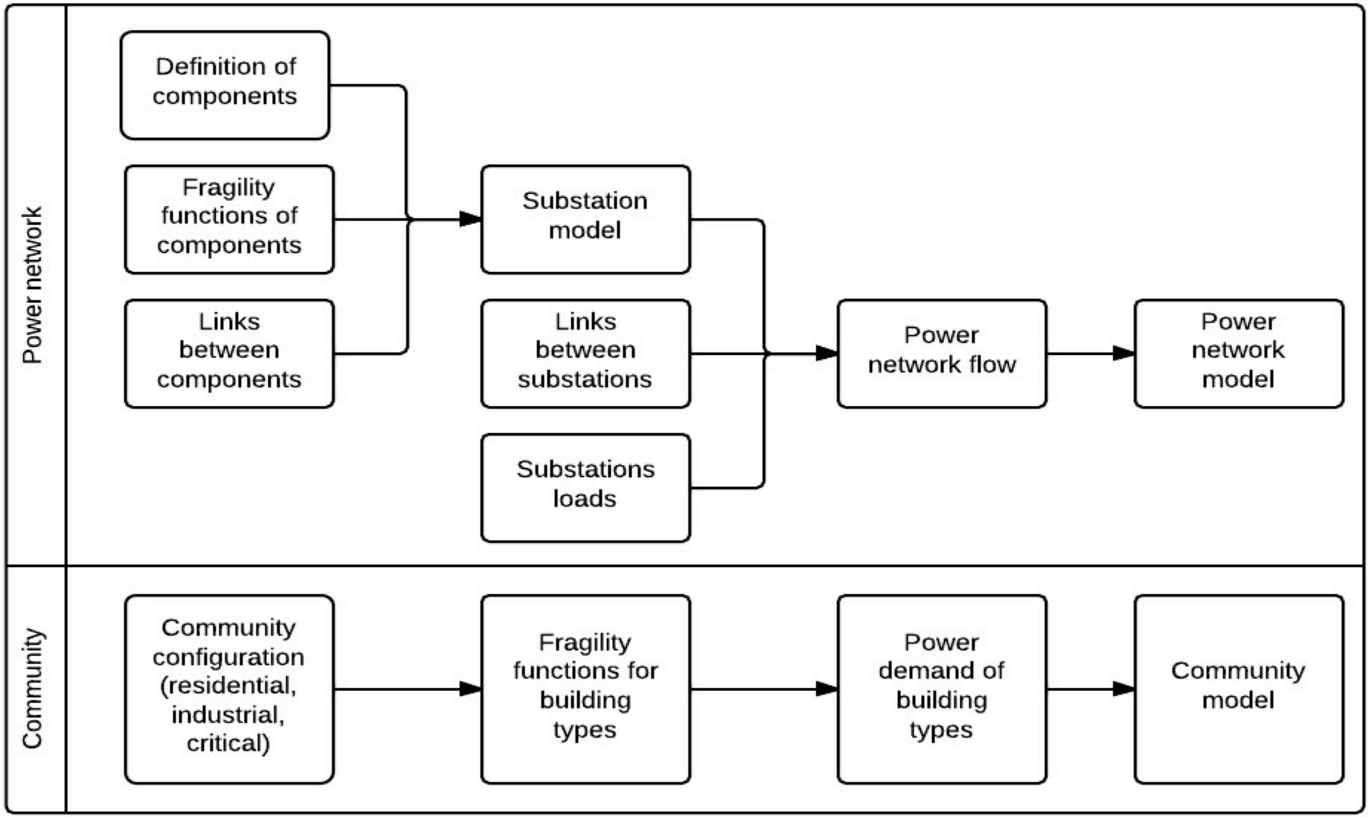
Application of Re-CoDeS

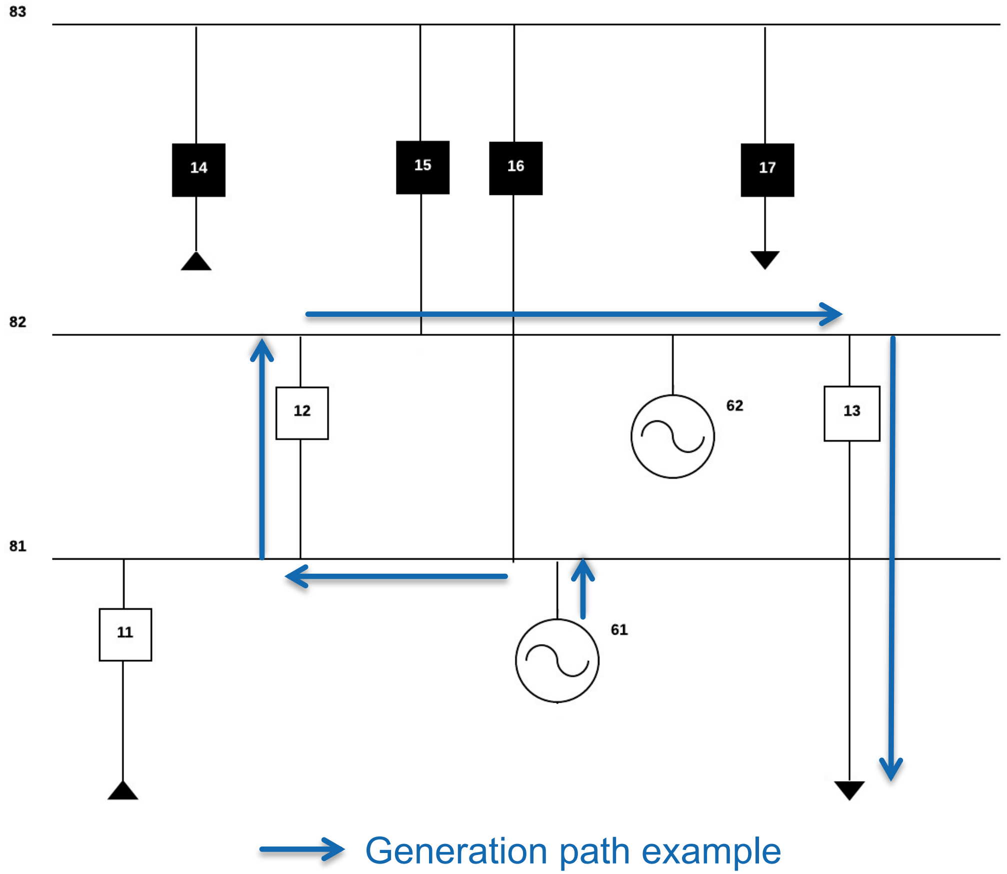
Power network & Community model



Methodology

Power network model: substations

Generation substation



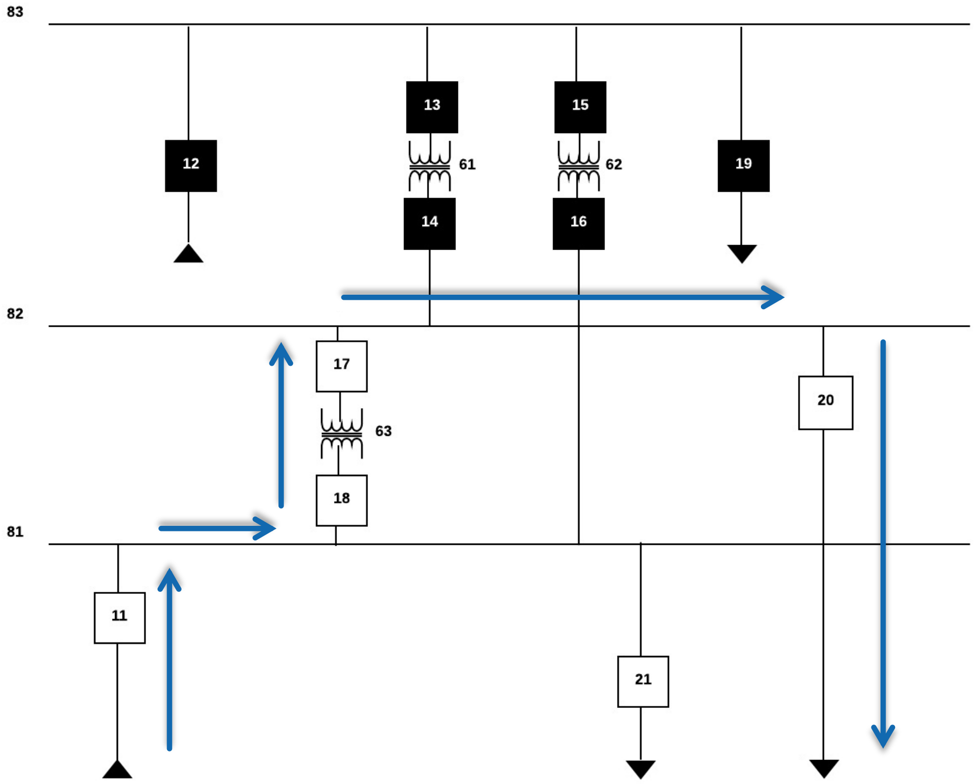
→ Generation path example

- Reserve bus bar not in operation in normal conditions
- All path possibilities for generation and transit of electricity are evaluated
- If any component on a path fails, that path is “failed”
- No electricity generation if: (1) generator failure or (2) no path available to get electricity out
- No electricity transit if: no path available to transit power flow

Methodology

Power network model: substations

Distribution substation



→ Transformation path example

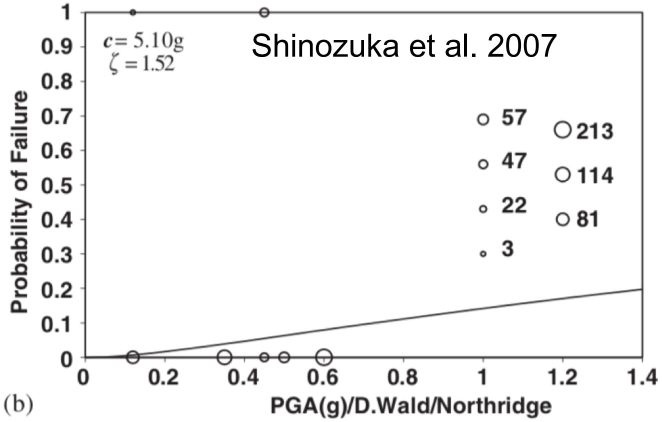
- Reserve bus bar not in operation in normal conditions
- All path possibilities for transformation and transit of electricity are evaluated
- If any component on a path fails, that path is “failed”
- No electricity transformation if: no path available to transform electricity
- No electricity transit if: no path available to transit power flow

Application of Re-CoDeS

Electric Power Supply System

- Substations modelled on a component level, lognormal fragility functions using the PGA as intensity measure
- Vulnerability of links not considered, transmission losses neglected

Component type	fragility functions		
	λ	β	source
small generation plant DS2	-1.77	0.5	FEMA 2003
small generation plant DS3	-0.87	0.5	FEMA 2003
circuit breaker	1.63	1.52	Shinozuka et al. 2007
transformer	-0.8	0.42	Shinozuka et al. 2007
bus bar	-0.37	1.20	Shinozuka et al. 2007


Shinozuka et al. 2007

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Application of Re-CoDeS

Electric Power Supply System

- Lognormal component recovery functions, conditioned on the initial component damage state & time since disaster (Didier et al. 2015)
- Probabilistic approach:
  - Formulation as conditional probability

$$RF = P(Q \geq q_{lim} | t)$$

RF: recovery function
Q: measure of functionality
q_{lim}: threshold parameter

Component type	recovery functions	
	mean [days]	st.dev. [days]
small generation plant DS2	2	0.75
small generation plant DS3	6	1.5
circuit breaker	4.8	2.25
transformer	4.8	2.25
bus bar	4.8	2.25

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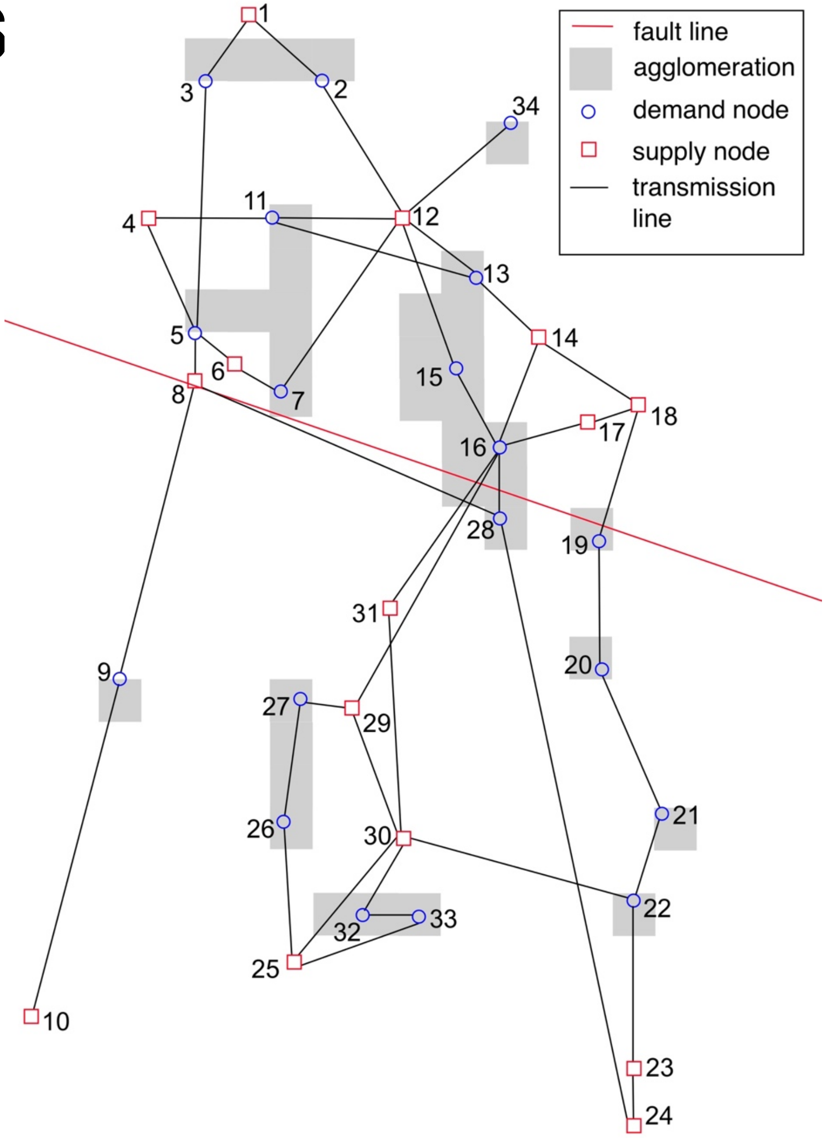
Application of Re-CoDeS

System Service Model

- Simplified electricity flow model to dispatch the electric power capacity to satisfy the service demand at the demand nodes in the undamaged and damaged system
- Prioritization strategy: supplying first nodes with low available supply but high demand



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Application of Re-CoDeS

Community Demand

- Two cities, several industrial zones, small villages, total population: approx. 600’000
- Community composed of: residential buildings, businesses, industrial facilities, critical facilities (hospitals & schools), seismic fragility modeled by fragility curves conditioned on the PGA
- Recovery: Weibull component recovery functions (Didier et al. 2015)
- Mean electric power demand associated to each building, depending on building type, occupancy state and damage state (Didier et al. 2017)

Occupancy type	DS1	DS2	DS3
Residential/ office	100%	$DRF_{c,res} * \left(1 - k_{res} * DRF_{l,res}\right) = 0.9 * (1 - \frac{\#buildings_{DS3,local}}{\#\ buildings_{local}})$	0%
Industrial facility	100%	$DRF_{c,ind} * \left(1 - k_{ind} * DRF_{l,ind}\right) = 0.9 * (1 - 2 * \frac{\#buildings_{DS3,total}}{\#buildings_{total}})$	0%
Critical facility	100%	100%	0%

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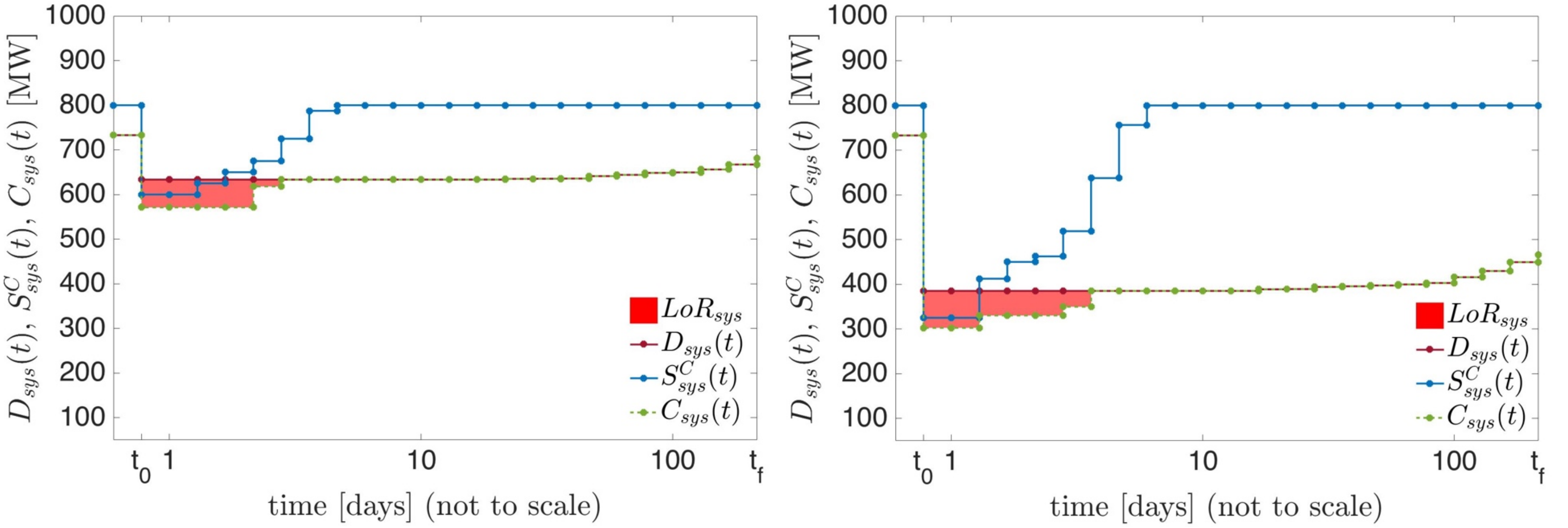
Application of Re-CoDeS

Results

t_0 : occurence of the earthquake,
t_f : 1 year after the occurrence of the earthquake
Monte Carlo simulation: 10’000 runs



1 realization of $M_w = 6$

1 realization of $M_w = 7$

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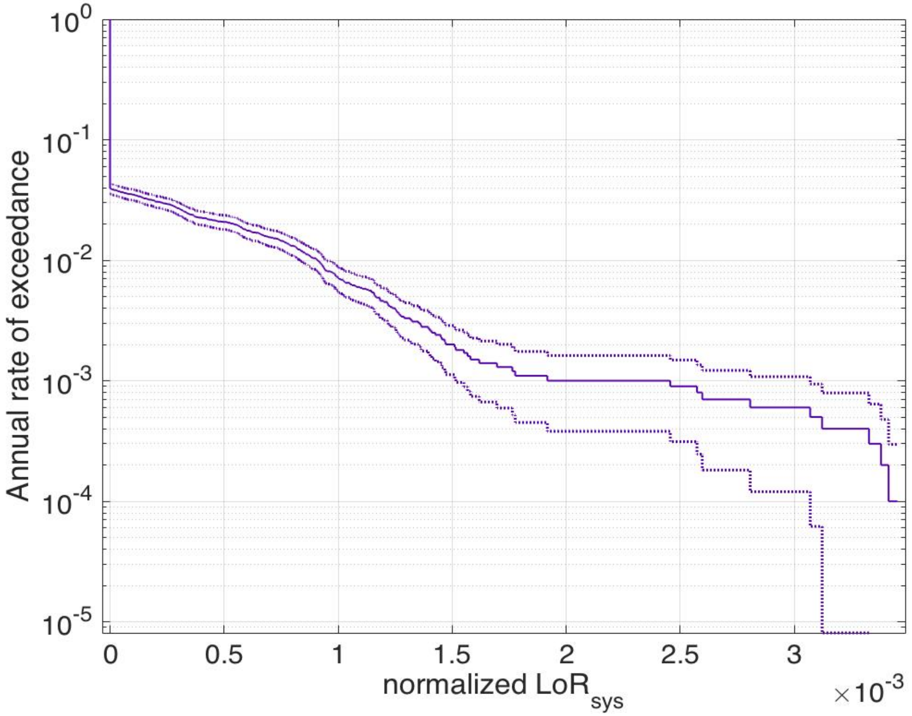
Application of Re-CoDeS

Results

- Annual rate of exceedance of the Lack of Resilience of the considered EPSS-community system



Mean $\widehat{LoR}_{sys} = 2.88 * 10^{-5}$

Expected Resilience

$R = 1 - \widehat{LoR}_{sys} = 0.9999712$

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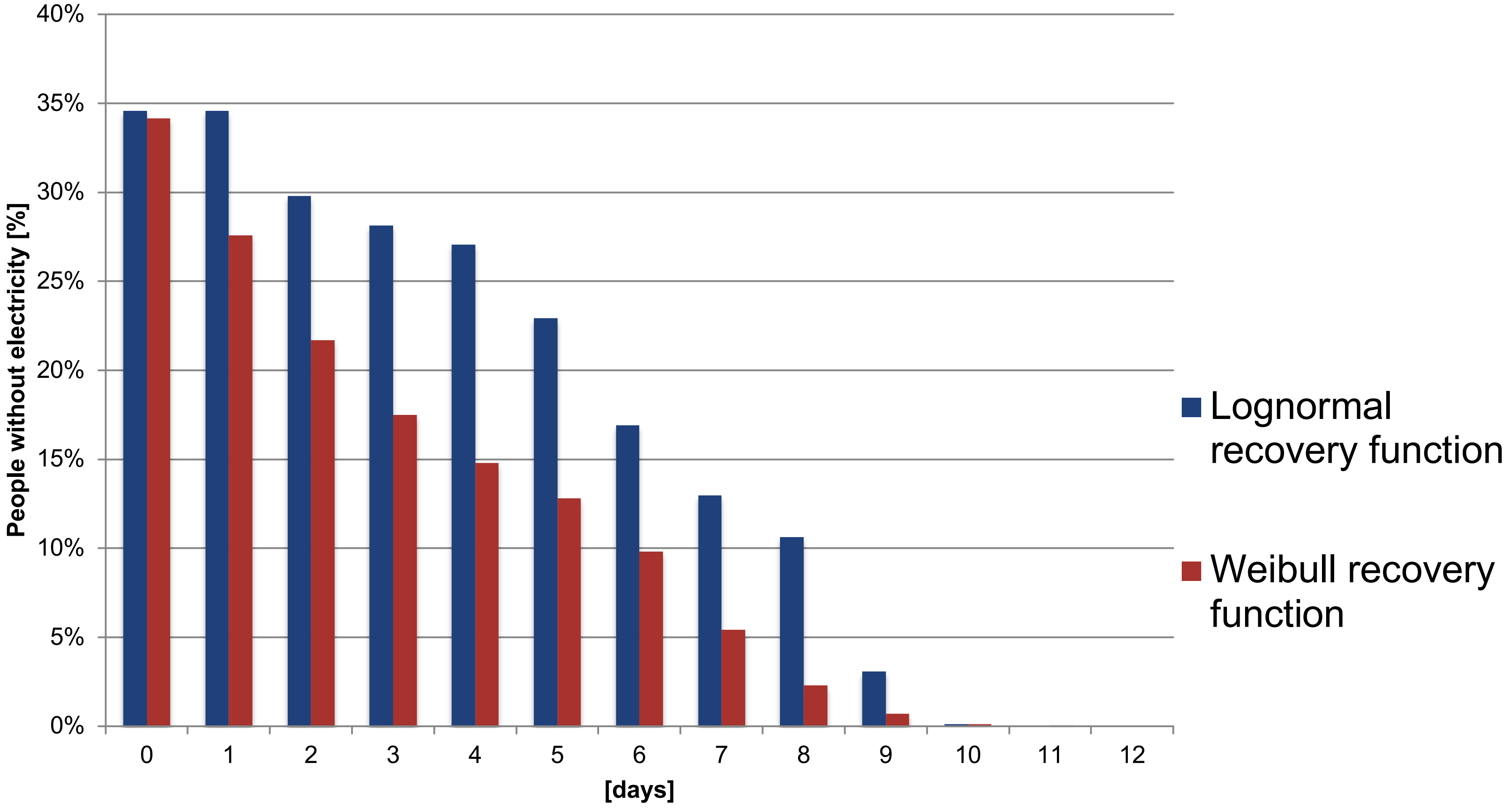
Application of Re-CoDeS

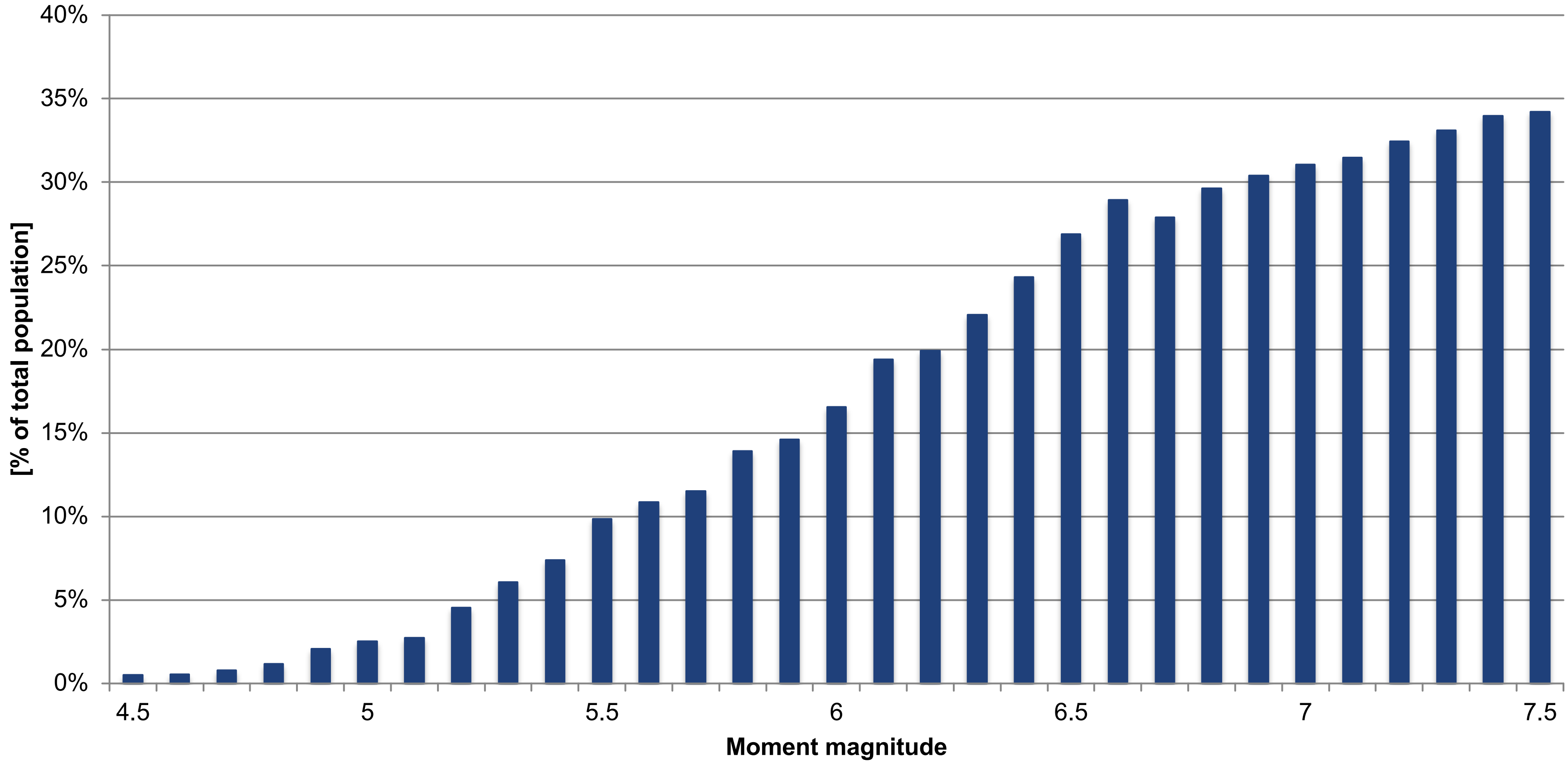
Results



Percentage of people affected by power outage for an earthquake of magnitude M=7.5

Application of Re-CoDeS

Results

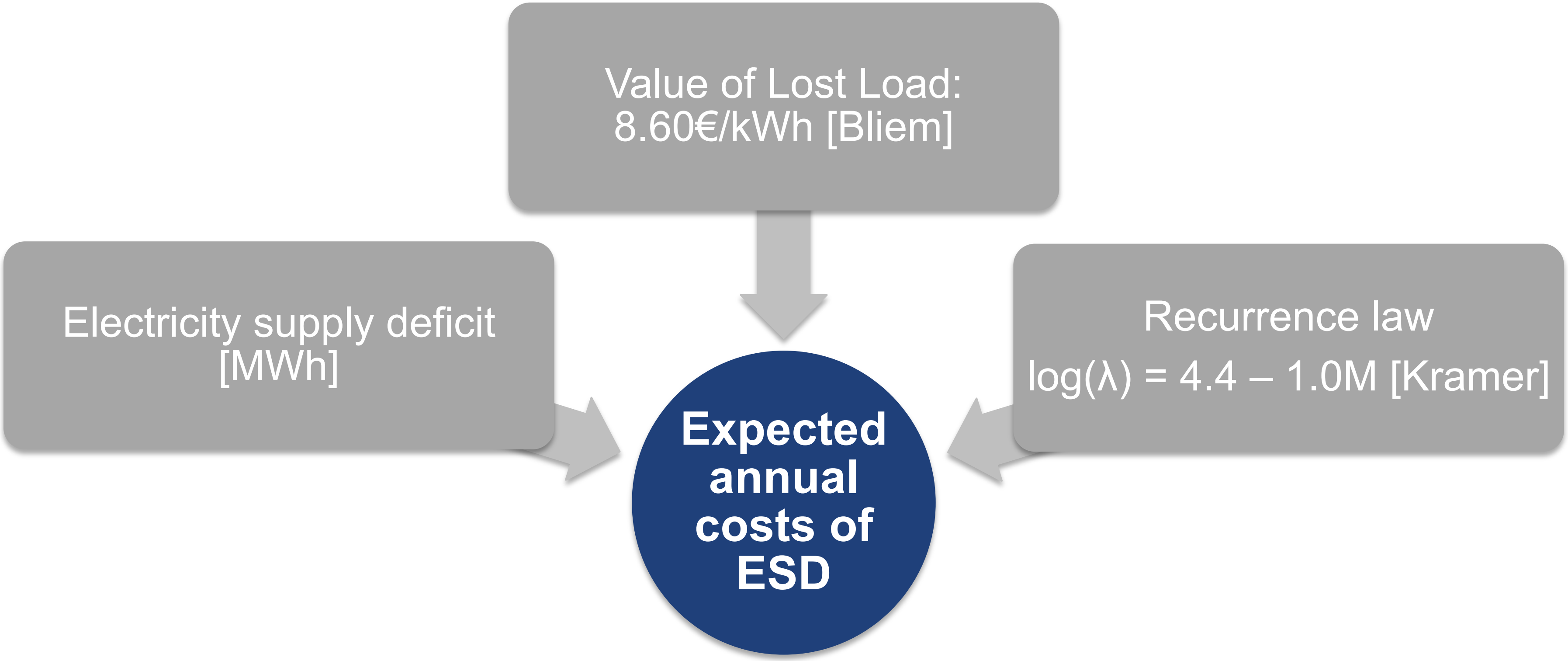


Percentage of total population without electric power after day 1 as a function of moment magnitude

Application of Re-CoDeS

Economic aspect of resilience: Electric supply deficit (ESD)

Electricity supply deficit = area between electric supply and theoretical demand curve (if supply is lower than demand



Value of Lost Load:
8.60€/kWh [Bliem]

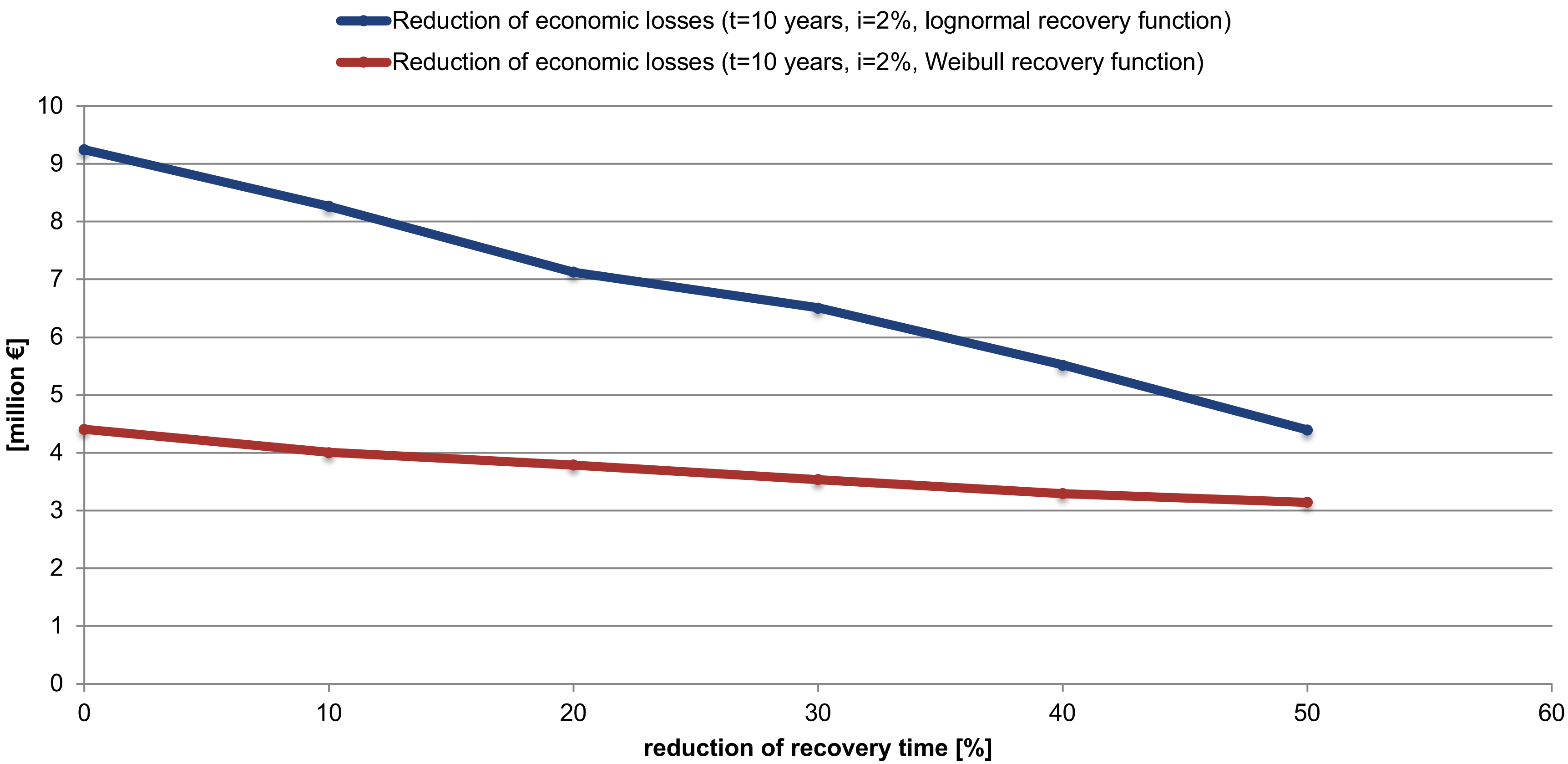
Electricity supply deficit
[MWh]

Recurrence law
$\log(\lambda) = 4.4 – 1.0M$ [Kramer]

Expected annual costs of ESD

Application of Re-CoDeS

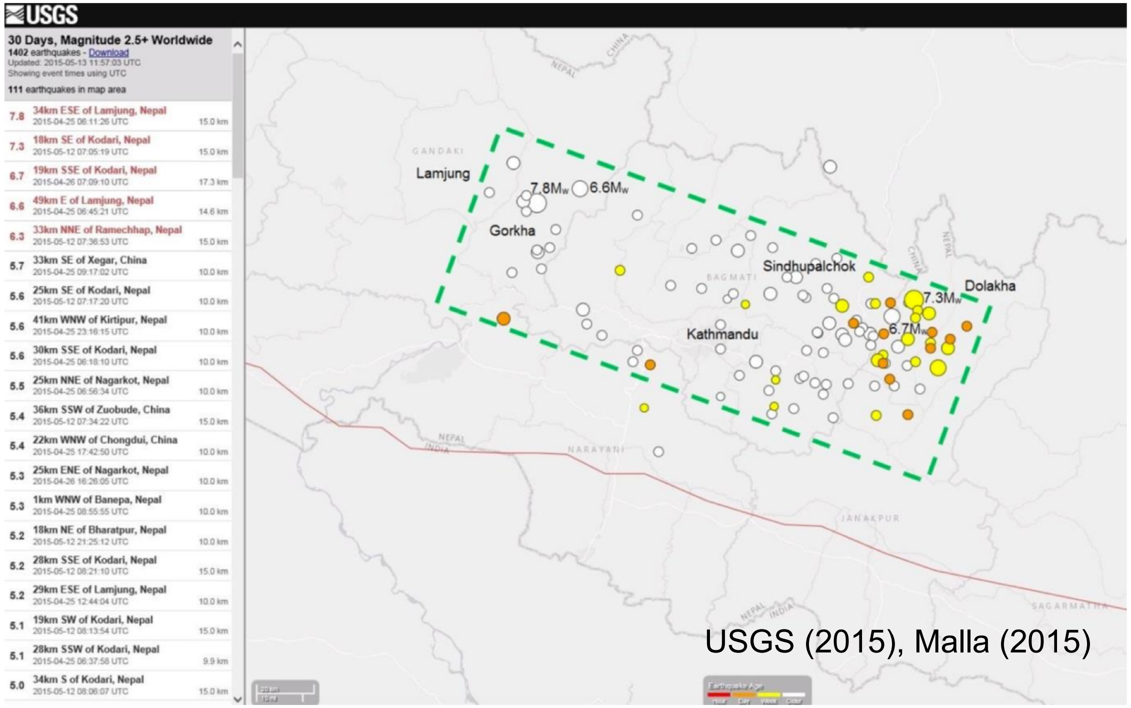
Economic aspect of resilience: Expected annual costs of electric supply deficit (ESD) as a function of reduction of recovery time



Comparison of expected annual costs of ESD as a function of reduction of recovery time of transformers in distribution substations between lognormal and Weibull recovery functions

Application of Re-CoDeS

- 2015 Gorkha (Nepal) earthquake
  - April 25, 2015: moment magnitude (M_w) 7.8 mainshock
  - May 12, 2015: major aftershock (M_w 7.3)
  - 9,000 deaths, 22,000 people injured, extensive damage to CISs and building stock



30 Days, Magnitude 2.5+ Worldwide
1402 earthquakes - Download
Updated: 2015-05-13 11:57:03 UTC
Showing event times using UTC

111 earthquakes in map area

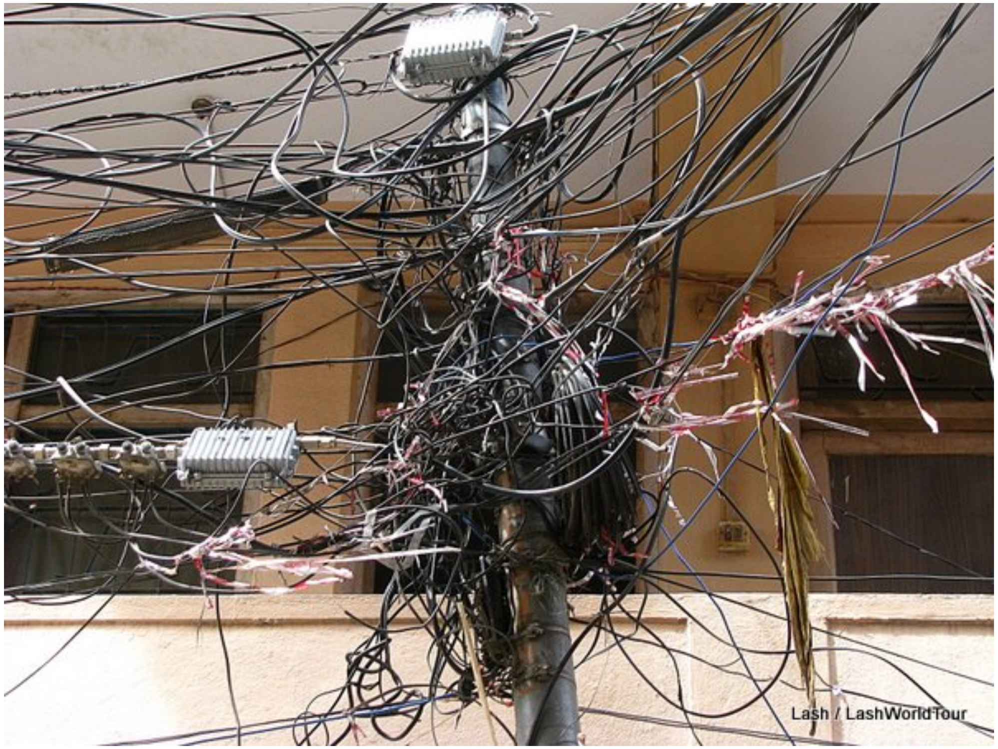
7.8	34km ESE of Lamjung, Nepal	2015-04-25 06:11:26 UTC	15.0 km
7.3	18km SE of Kodari, Nepal	2015-05-12 07:05:19 UTC	15.0 km
6.7	19km SSE of Kodari, Nepal	2015-04-26 07:09:10 UTC	17.3 km
6.6	49km E of Lamjung, Nepal	2015-04-25 06:45:21 UTC	14.6 km
6.3	33km NNE of Ramechhap, Nepal	2015-05-12 07:36:53 UTC	15.0 km
5.7	33km SE of Xegar, China	2015-04-25 09:17:02 UTC	10.0 km
5.6	25km SE of Kodari, Nepal	2015-05-12 07:17:20 UTC	10.0 km
5.6	41km WNW of Kirtipur, Nepal	2015-04-25 23:16:15 UTC	10.0 km
5.6	30km SSE of Kodari, Nepal	2015-04-25 06:18:10 UTC	10.0 km
5.5	25km NNE of Nagarkot, Nepal	2015-04-25 06:56:34 UTC	10.0 km
5.4	36km SSW of Zuobude, China	2015-05-12 07:34:22 UTC	15.0 km
5.4	22km WNW of Chongdui, China	2015-04-25 17:42:50 UTC	10.0 km
5.3	25km ENE of Nagarkot, Nepal	2015-04-26 16:26:05 UTC	10.0 km
5.3	1km WNW of Banepa, Nepal	2015-04-25 08:55:55 UTC	10.0 km
5.2	18km NE of Bharatpur, Nepal	2015-05-12 21:25:12 UTC	10.0 km
5.2	28km SSE of Kodari, Nepal	2015-05-12 08:21:10 UTC	15.0 km
5.2	29km ESE of Lamjung, Nepal	2015-04-25 12:44:04 UTC	10.0 km
5.1	19km SW of Kodari, Nepal	2015-05-12 08:13:54 UTC	15.0 km
5.1	28km SSW of Kodari, Nepal	2015-04-25 06:37:58 UTC	9.9 km
5.0	34km S of Kodari, Nepal	2015-05-12 08:06:07 UTC	15.0 km

USGS (2015), Malla (2015)

- Assessment of the resilience during the events of the cellular communication system, the electric power supply system and the water supply system using data collected/obtained from stakeholders, on-site visits, experts interviews etc…

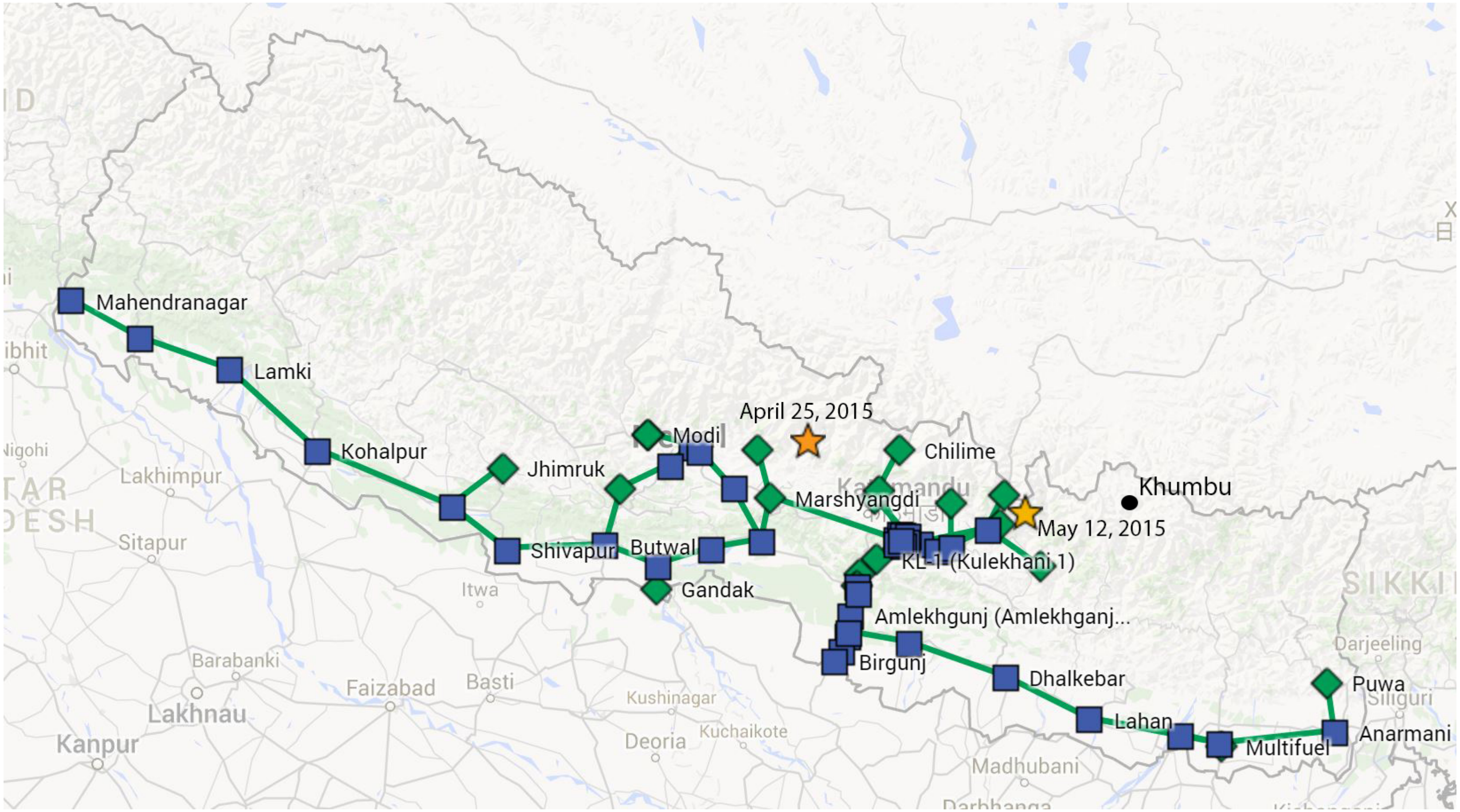
Resilience of the Electric Power Supply System

Damage



Resilience of the Electric Power Supply System

Topology of the INPS



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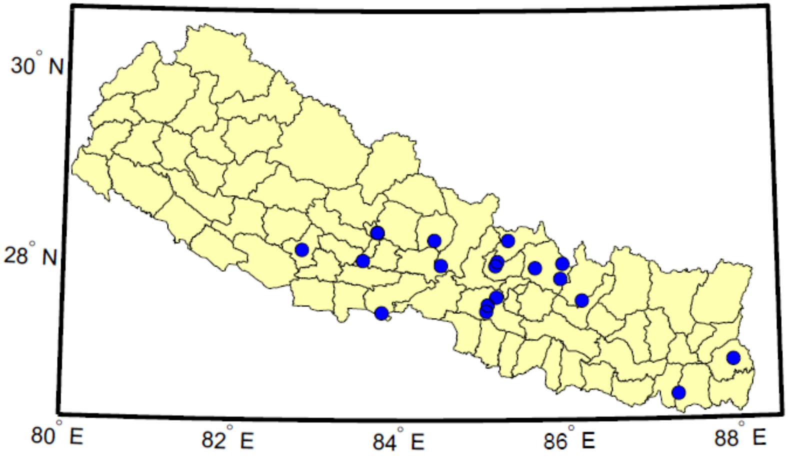
Resilience of the Electric Power Supply System

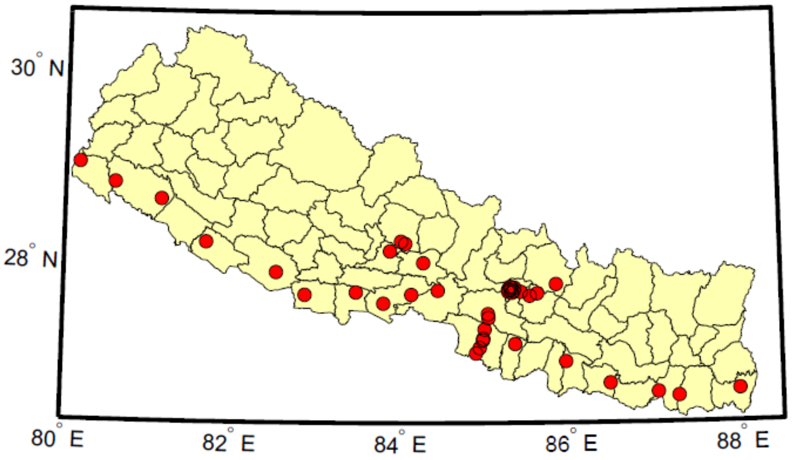
Nepalese Power Supply System

- On-grid system:
  - 17 large hydropower plants
  - 40+ small hydropower plants
  - 2 thermal power plants
  - 2 solar power plants
- 30 power plants, 8 distribution substations were damaged
- Damages included:
  - Cracks in hydropower dams, power houses, waterways, boundary walls, columns, beams, foundations of substation buildings
  - Equipment damage (transformer displacement, oil leakages)
  - Broken transmission lines (≈ 2100 km)

Generation substation locations (Power plants)



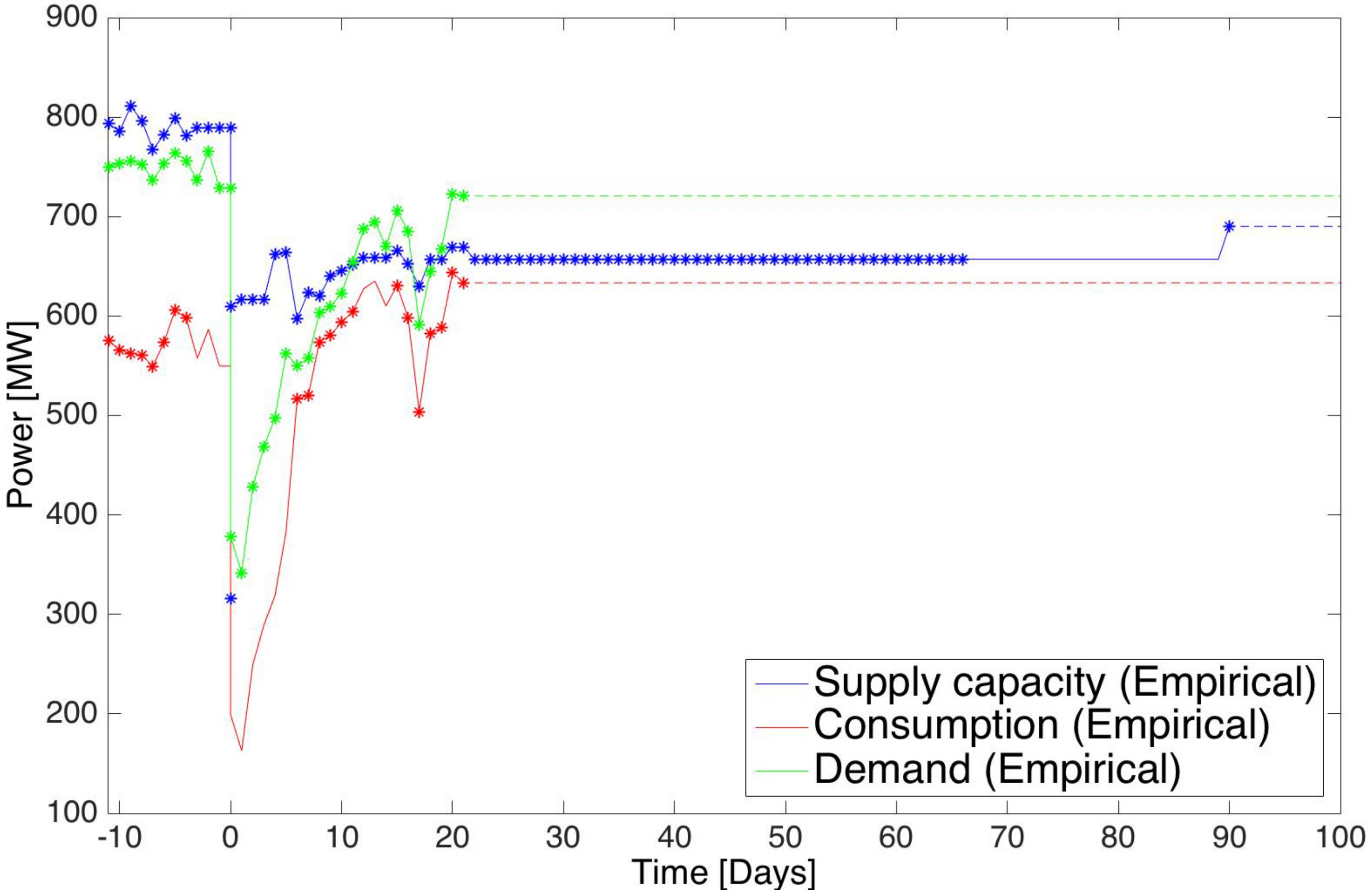
Distribution substation locations



Didier, M., Grauvogl, B., Steentoft, A., Broccardo, M., Ghosh, S. and Stojadinovic, B. (2017). Seismic Resilience of the Nepalese Power Supply System during the 2015 Gorkha Earthquake. 16th World Conference on Earthquake Engineering, January 9-13, 2017. Santiago de Chile, Chile.

Resilience of the Electric Power Supply System

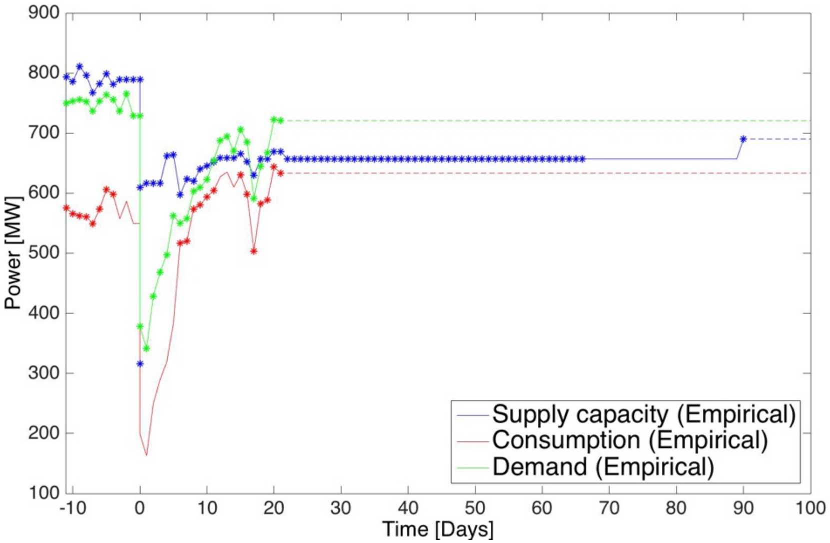
Resilience of the INPS during the 2015 Gorkha Earthquake

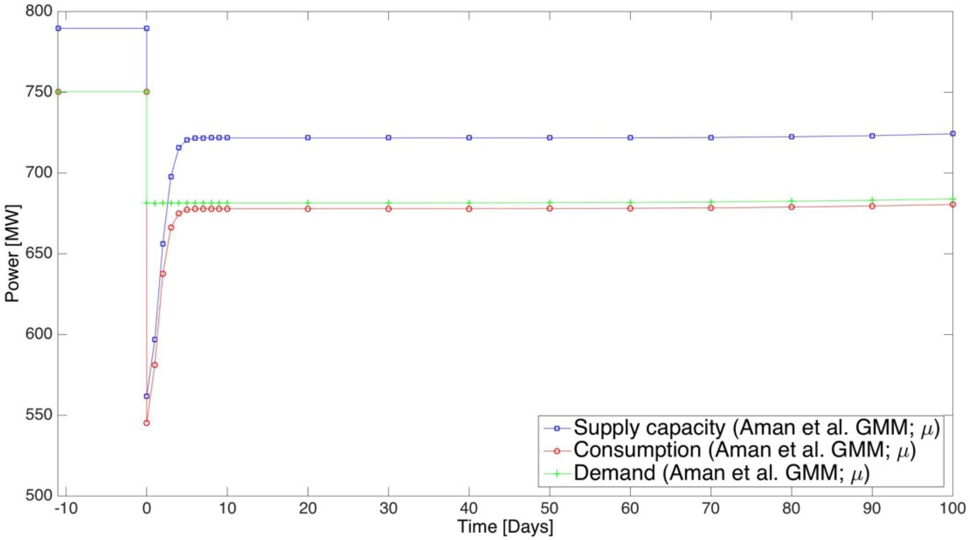


Didier, M., Grauvogl, B., Steentoft, A., Broccardo, M., Ghosh, S. and Stojadinovic, B. (2017). Seismic Resilience of the Nepalese Power Supply System during the 2015 Gorkha Earthquake. 16th World Conference on Earthquake Engineering, January 9-13, 2017. Santiago de Chile, Chile.

Resilience of the Electric Power Supply System

Resilience of the INPS – empirical vs. simulated

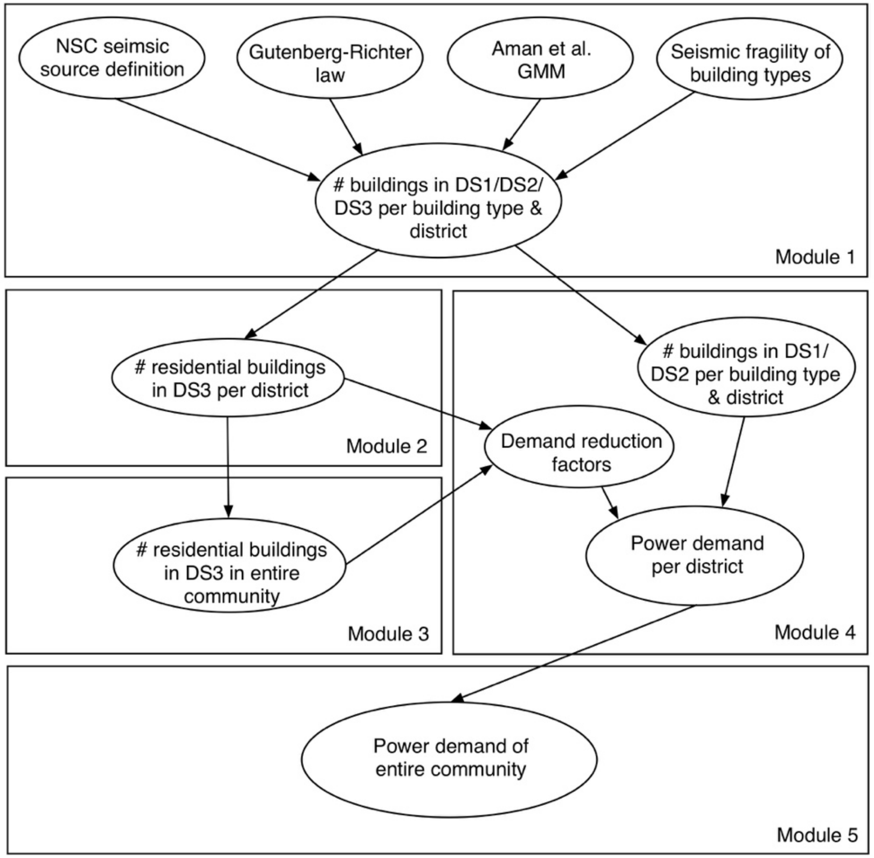




Didier, M., Grauvogl, B., Steentoft, A., Broccardo, M., Ghosh, S. and Stojadinovic, B. (2017). Seismic Resilience of the Nepalese Power Supply System during the 2015 Gorkha Earthquake. 16th World Conference on Earthquake Engineering, January 9-13, 2017. Santiago de Chile, Chile.

Examples

Modeling of power demand: Bayesian Probabilistic Networks (BPN)



Didier, M., Grauvogl, B., Steentoft, A., Broccardo, M., Ghosh, S. and Stojadinovic, B. (2017). Assessment of Post-Disaster Community Infrastructure Services Demand using Bayesian Networks. 16th World Conference on Earthquake Engineering, January 9-13, 2017. Santiago de Chile, Chile.

Conclusions

- *Re-CoDeS* can be used to **quantify** the **resilience of various civil infrastructure systems, including the electric power supply system**
- It explicitly accounts for both the vulnerability & recovery of the **service supply** and for the vulnerability & recovery **community demand** after a disaster
- A ***Lack of Resilience*** is observed when the service demand cannot be fully supplied
- **Normalized** measures allow a direct **comparison** between different systems
- The classification of resilience-related configurations may help to predict system behavior & to design more resilient CISs

Conclusions

- Using Re-CoDeS**, community risk mitigation strategies** can be **evaluated** and the **recovery optimized** to make **better use of scarce financial & human resources** in order to **increase community resilience toward a resilient 21st century**

<u>However</u>:

- **Large amount of data** and input **needed** to assess the resilience of the **complex socio-technical community system, integrating the knowledge of many research domains**
- **Toolbox** required that is modular & adaptable to different hazards, civil infrastructure systems, communities,… taking advantage of **advanced uncertainty quantification and machine learning methods** and accounting for **no data** & **big data** scenarios

Thank you for your attention!
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