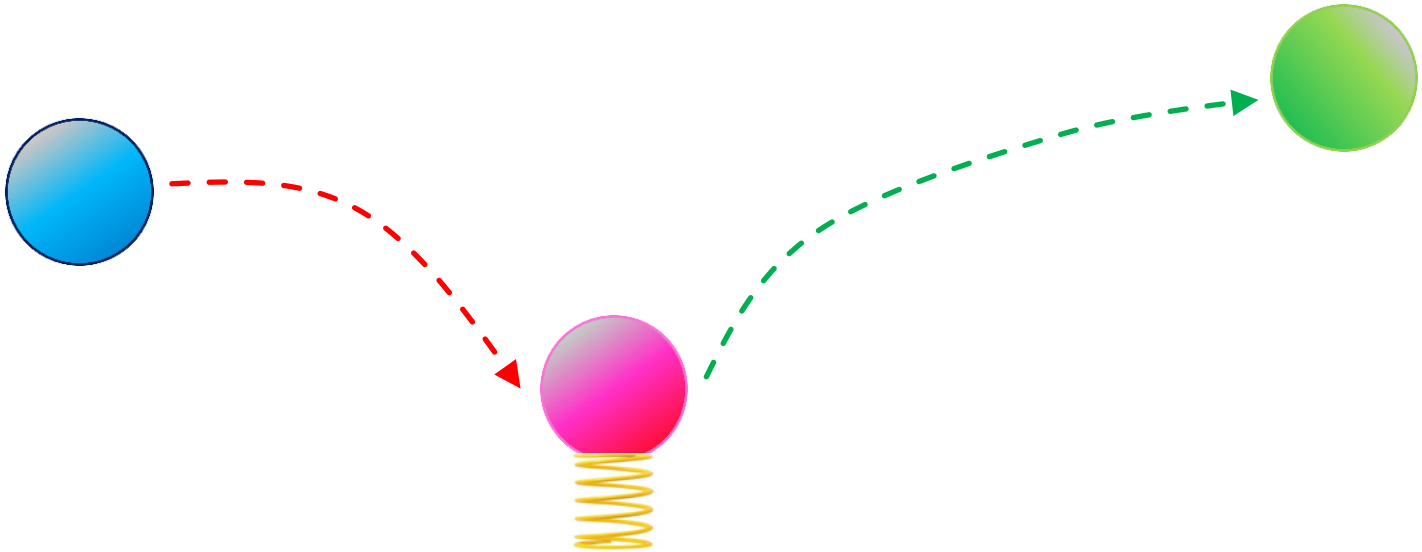
ETH zürich



Resilience-Based Design of Communities

Prof. Dr. Božidar Stojadinović

Chair of Structural Dynamics and Earthquake Engineering, ETH Zürich

Institute of Structural Engineering
Structural Dynamics and Earthquake Engineering Group

16TH EUROPEAN CONFERENCE ON
EARTHQUAKE ENGINEERING
THESSALONIKI
18 - 21 JUNE 2018

Surviving Natural Hazards…

http://willandjustingeo.weebly.com/natural-hazard-and-disaster.html
http://all-that-is-interesting.com/the-most-devastating-natural-disasters-of-the-21st
http://youth.wmo.int/met-subpages/natural-hazards-and-disasters
https://www.cbsnews.com/pictures/new-zealand-earthquake-november-2016/
http://www.eri.u-tokyo.ac.jp/KOHO/Yoran2001ep/07_1.html

… Necessitates Resilience

http://science.k12flash.com/naturalhazards.html

Resilience is a Desirable Property…
… of Structural Elements

https://fineartamerica.com/featured/ancient-greek-columns-or-pillars-iii-standing-tall-in-athens-greece-john-a-shiron.html

Resilience is a Desirable Property…
… of Stand-Alone Structures

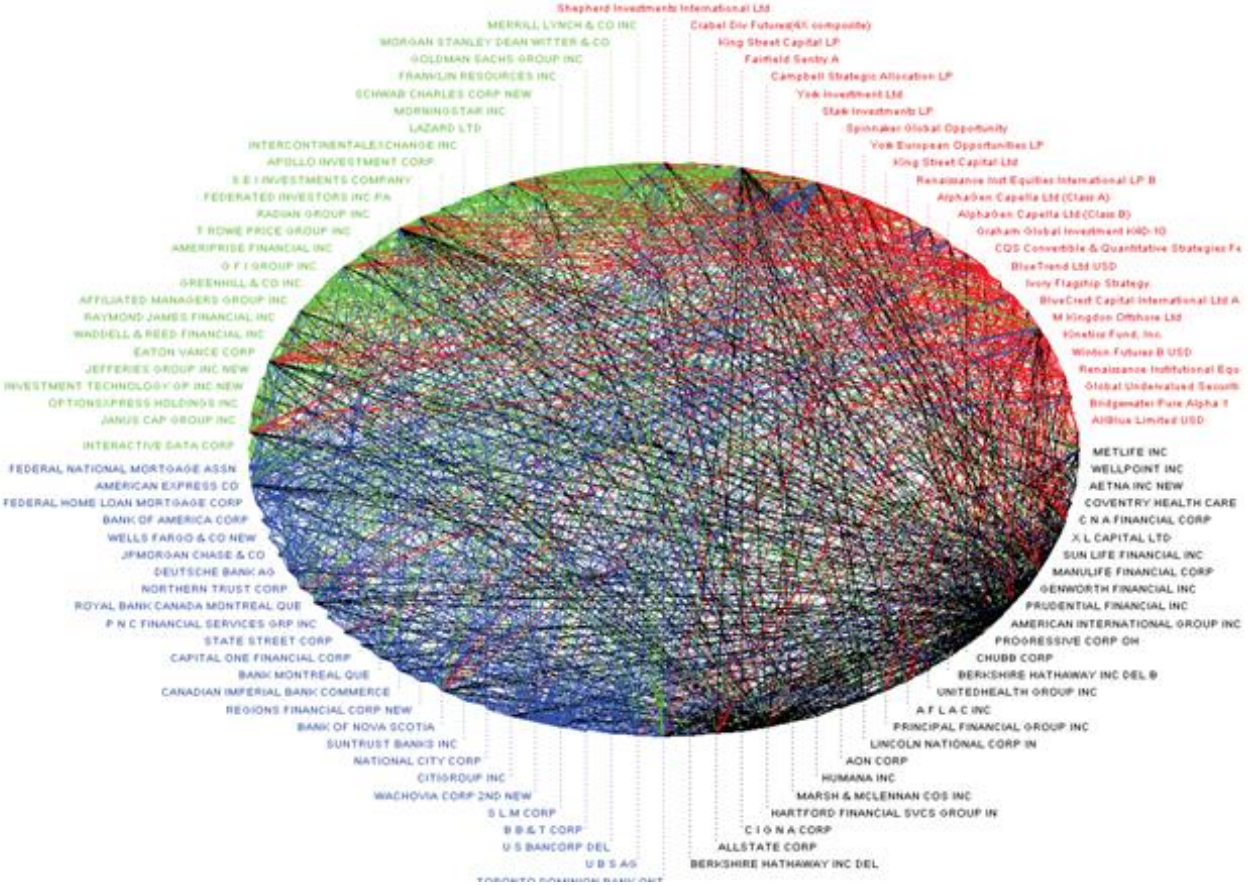
https://www.dreamstime.com/stock-photo-lonely-house-river-drina-bajina-basta-serbia-image72565378

Resilience is a Desirable Property…
… of Civil Infrastructure Systems

Resilience is a Desirable Property…
… of Mega-Cities

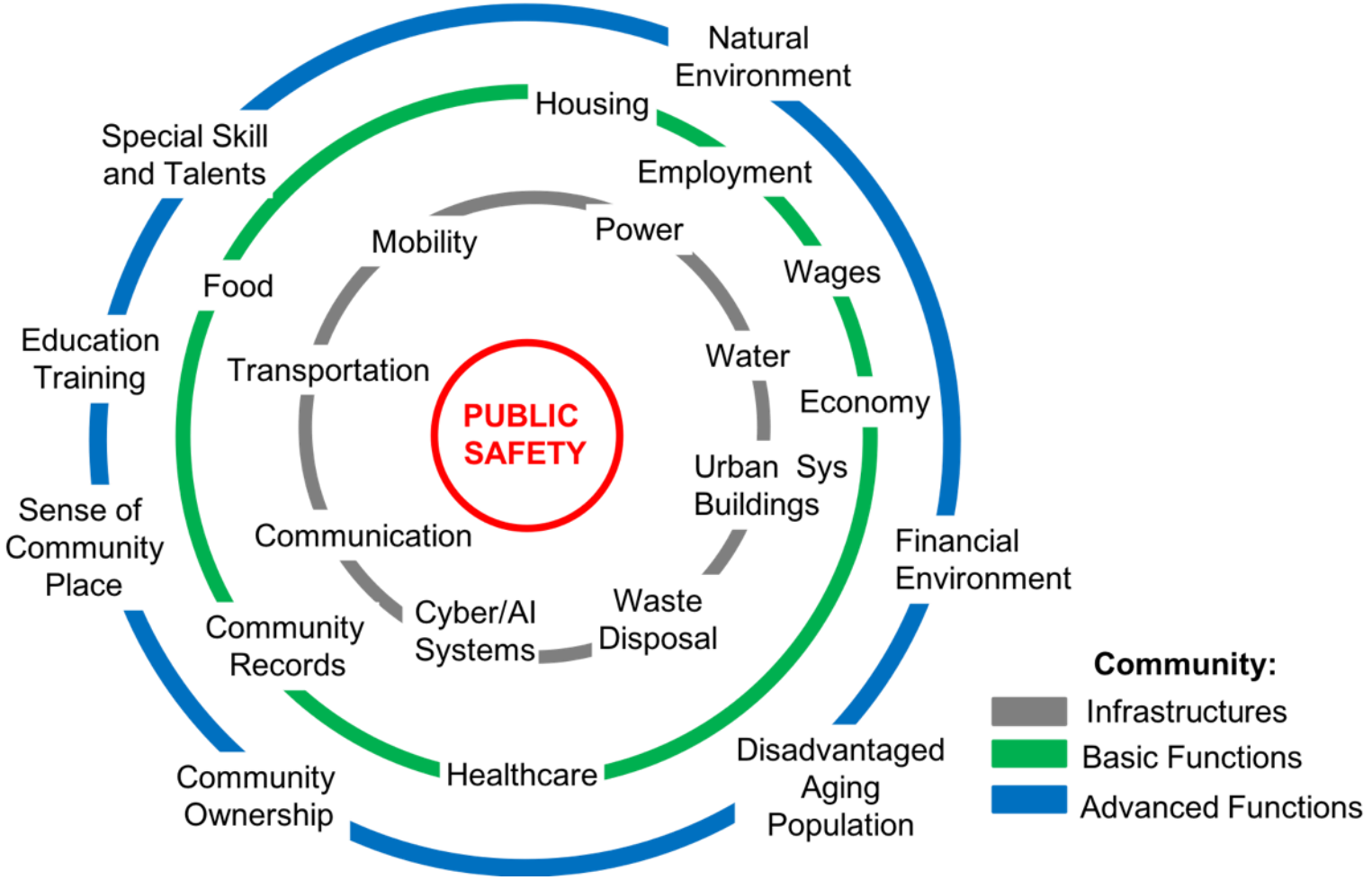
http://www.lifestyleasia.com/492223/futuristic-city-singapores-skyline-changed-past-decade/

Community Resilience is Systemic



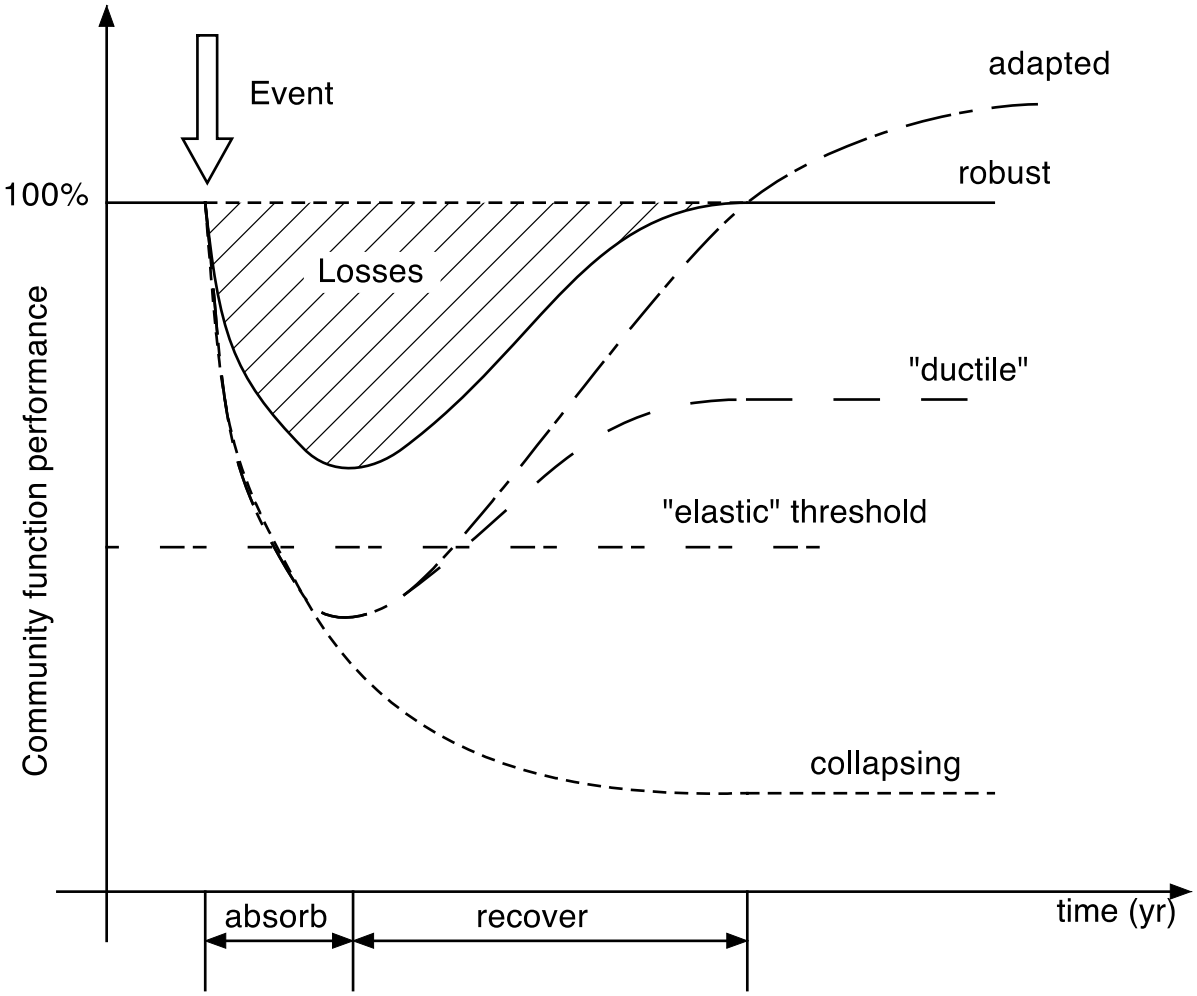
https://fitforrandomness.wordpress.com/2012/02/08/insurance-industry-super-spreaders-of-systemic-risk/

Community Functions

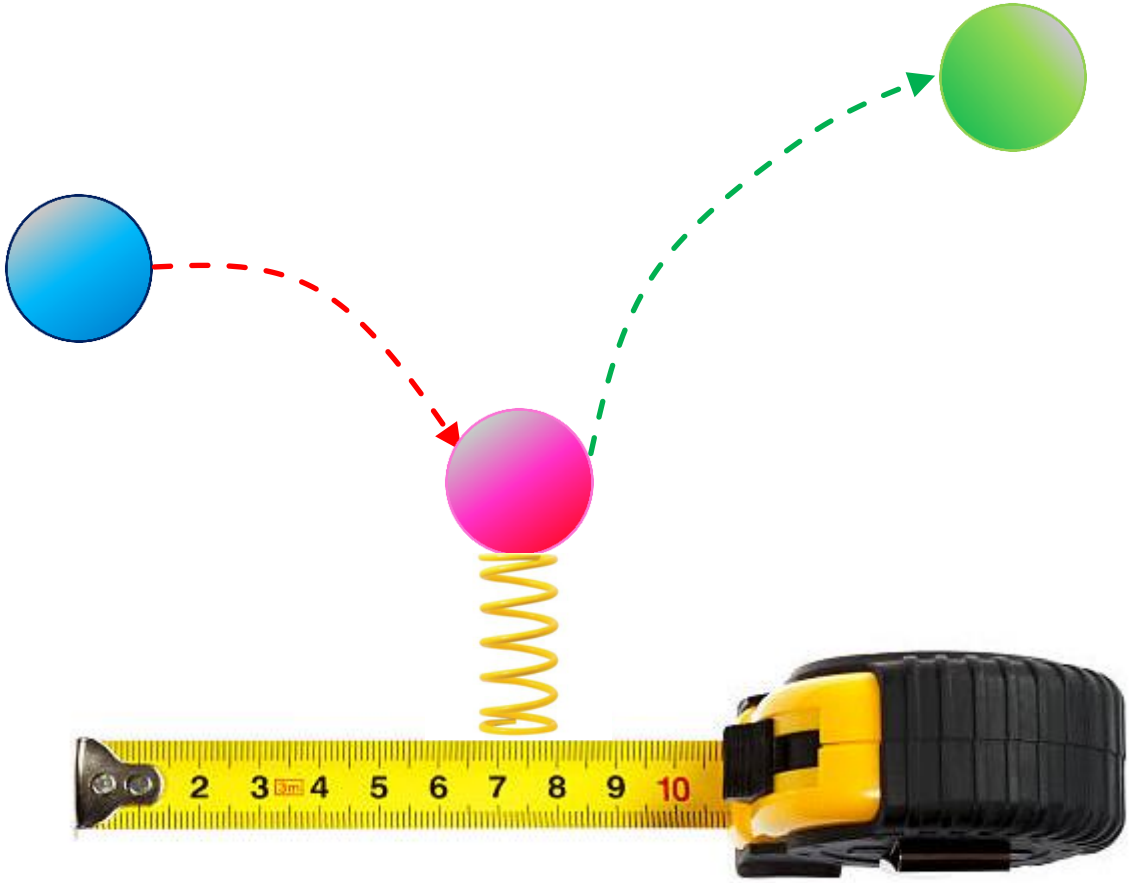


Important community functions (SERRI and CARRI, 2009)

Community Resilience is a Process



Measuring Community Resilience

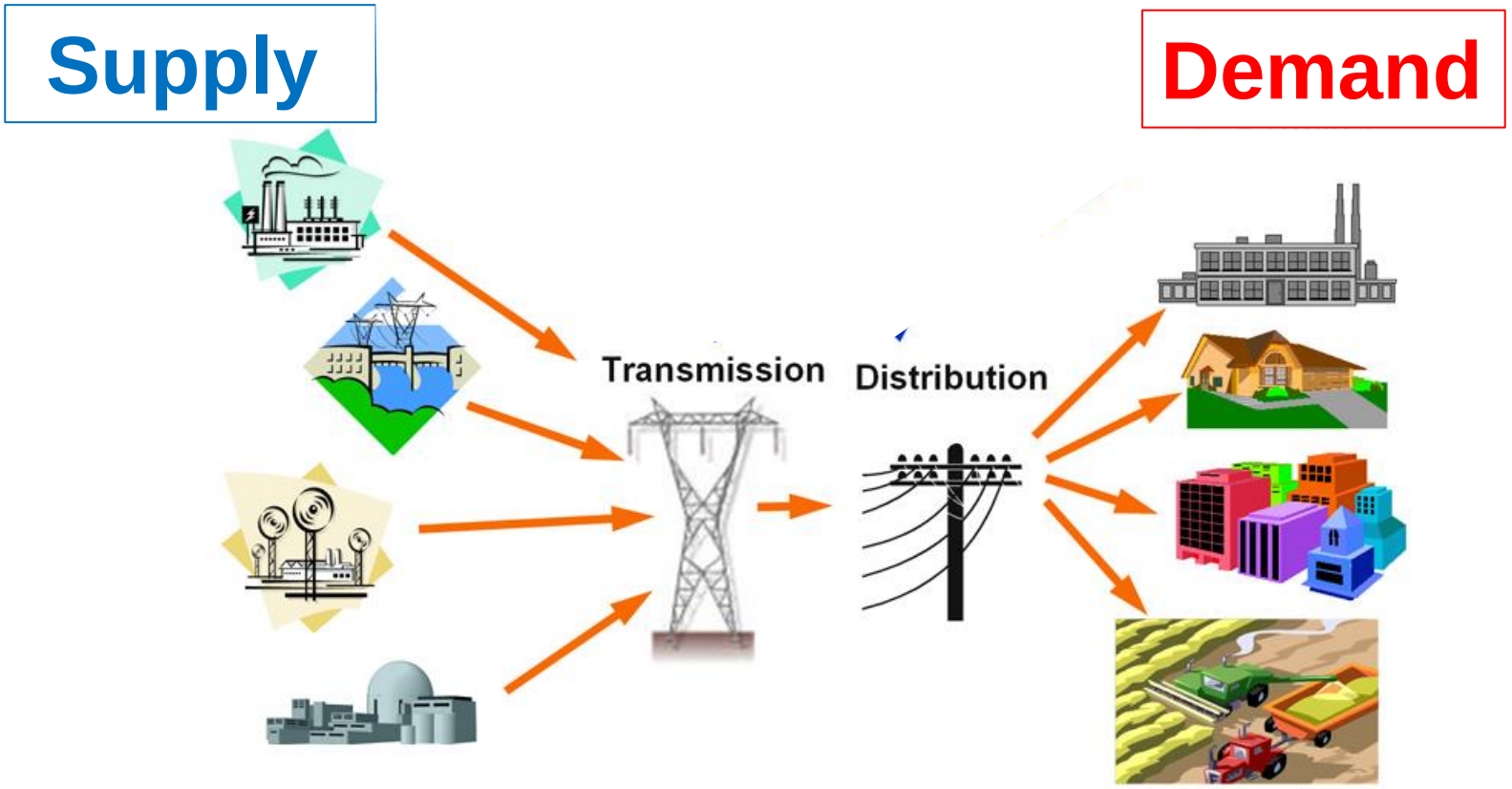


Service Supply vs. Service Demand

Electric Power
Supply System

Community
Power Consumption

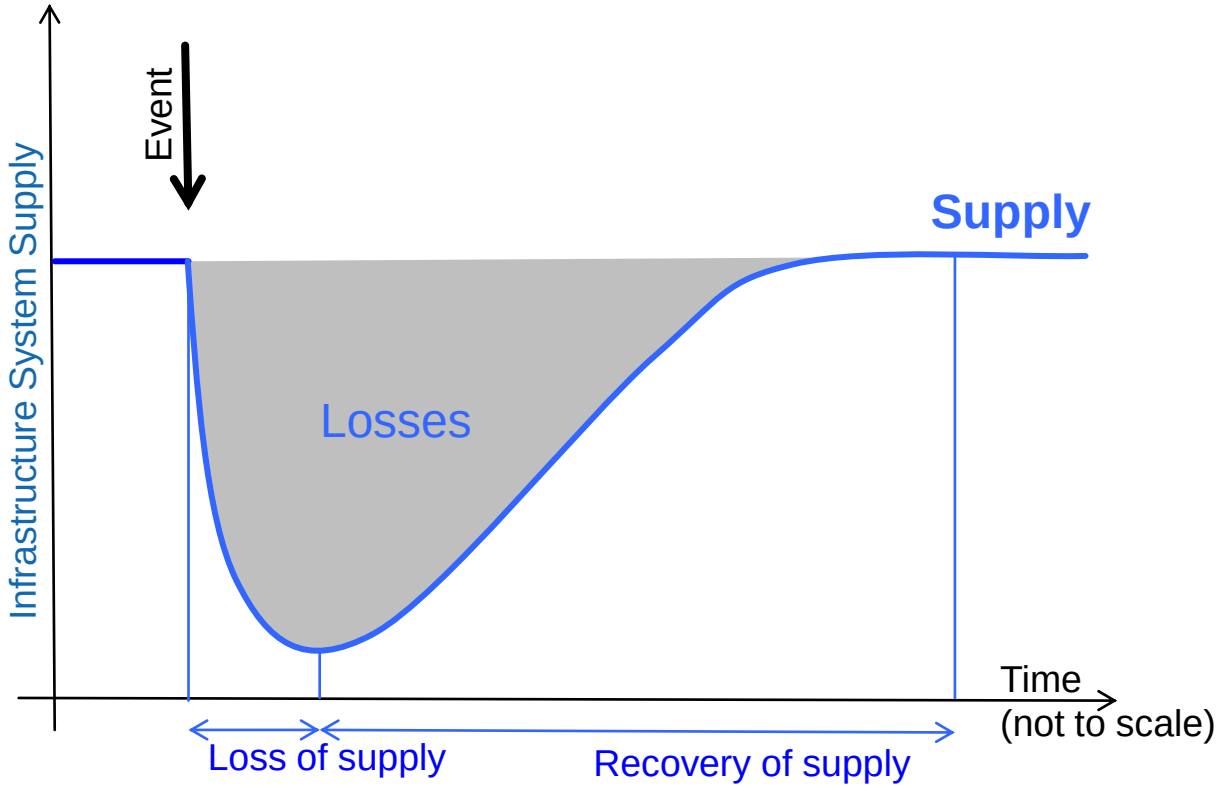
Service Supply/Demand Interaction for Civil Infrastructure Systems



http://ceeesa.es.anl.gov/images/ceeesa_ProjectsWECC_Climate_Power_Impacts_800.jpg

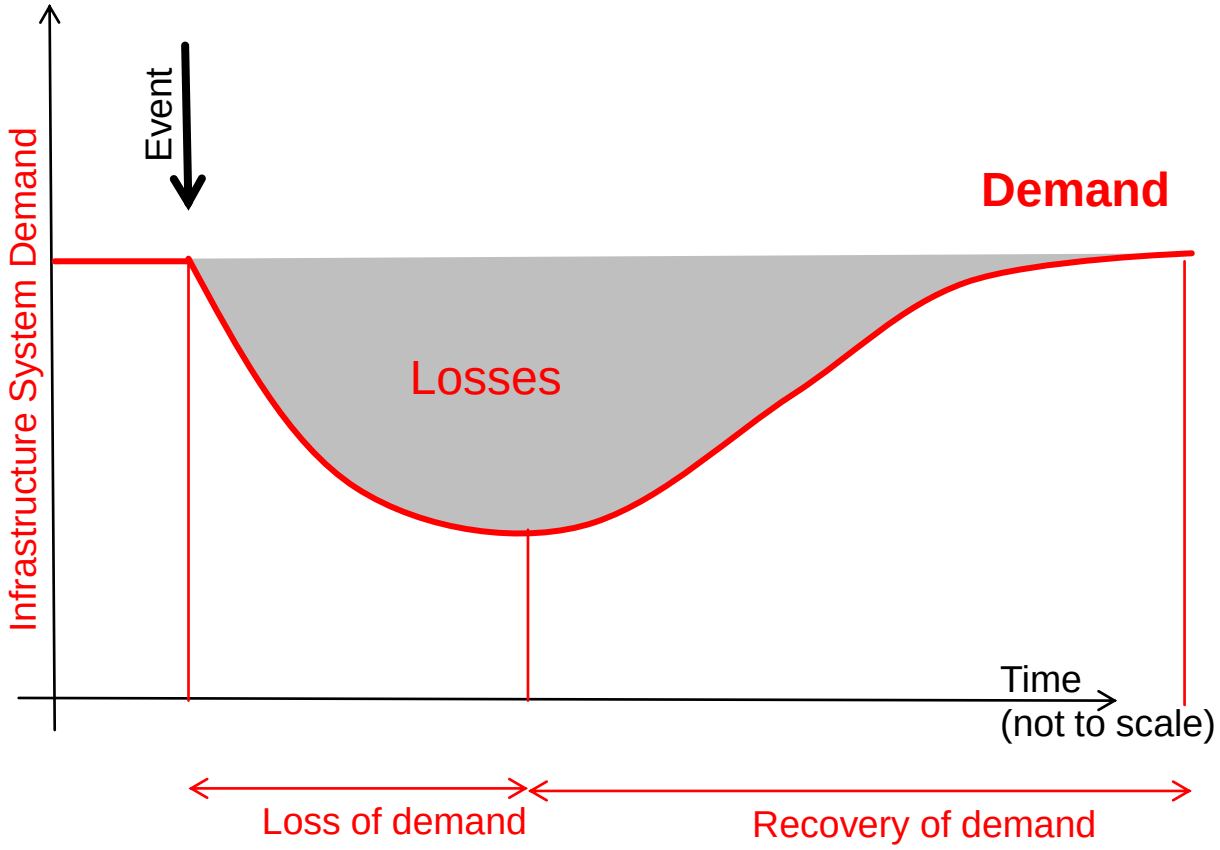
Service Supply for Civil Infrastructure Systems

- Infrastructure system supply:
  - Suffers an (instantaneous) drop when the event occurs
  - Recovers over time
  - Depends on the vulnerability and recovery of elements of community infrastructure



Service Demand for Civil Infrastructure Systems

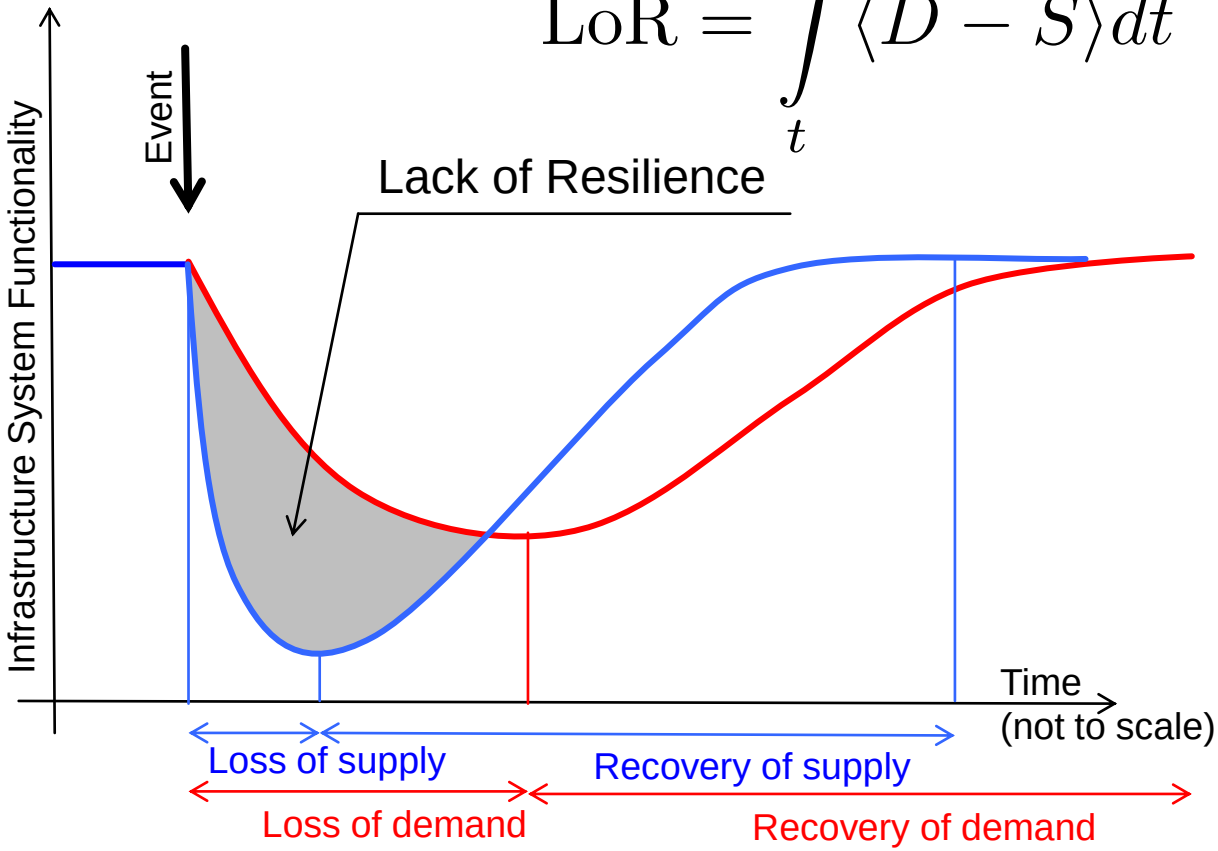
- Infrastructure system demand:
  - Suffers an (instantaneous) drop when the event occurs
  - Recovers over time
  - Depends on the vulnerability and recovery of elements of community infrastructure



Supply/Demand Formulation to Quantify Community Infrastructure Resilience

- Separately model the evolution of supply and demand
- Lack of resilience occurs when the supply cannot meet the demand
  - Different rates of supply and demand loss absorption and recovery matter!

$$\mathrm{LoR} = \int_t \langle D - S \rangle dt$$



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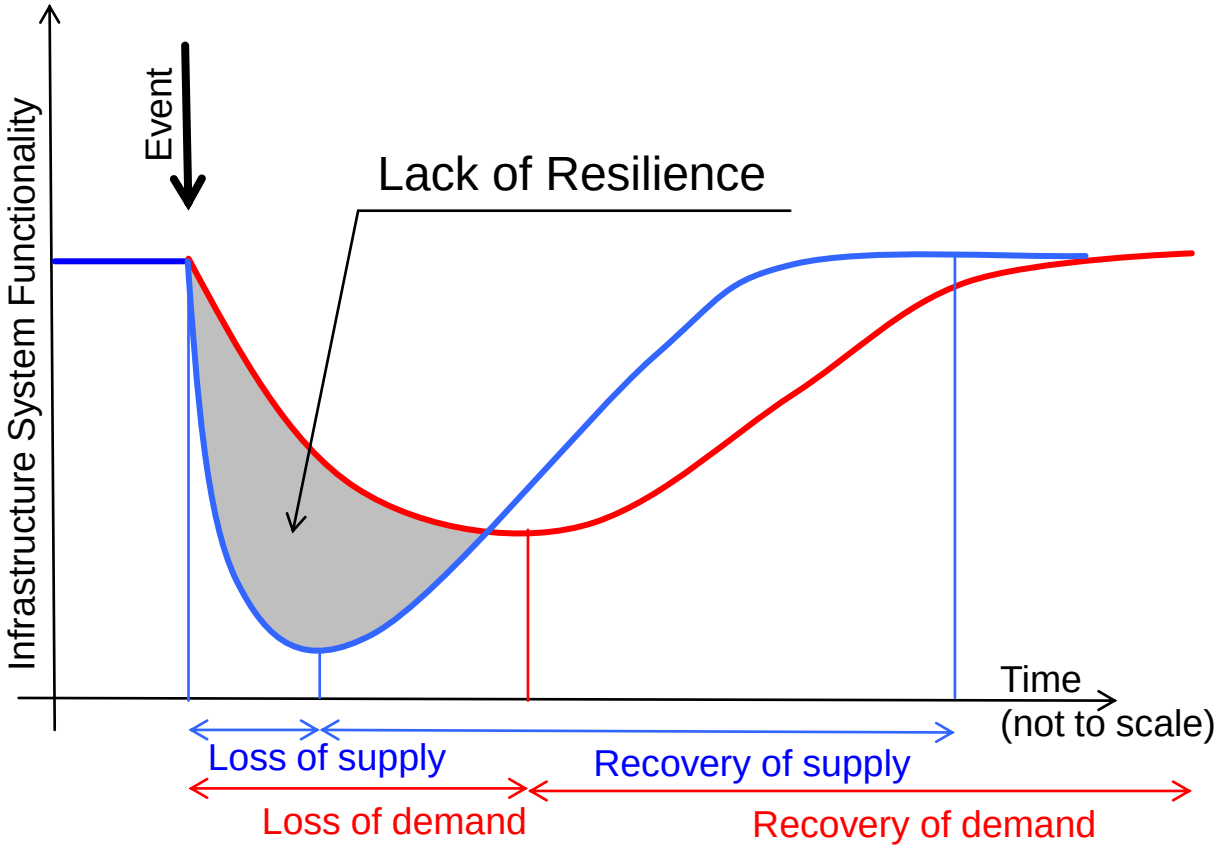
Didier M, Broccardo M, Esposito S, Stojadinovic B (2017). A Compositional Demand/Supply Framework to quantify the Resilience of Civil Infrastructure Systems (Re-CoDeS). *Sustainable and Resilient Infrastructure.*

Supply/Demand Formulation to Quantify Community Infrastructure Resilience

- How to compute this?

$$\mathrm{LoR} = \int_t \langle D - S \rangle dt$$

- **Re-CoDeS** framework



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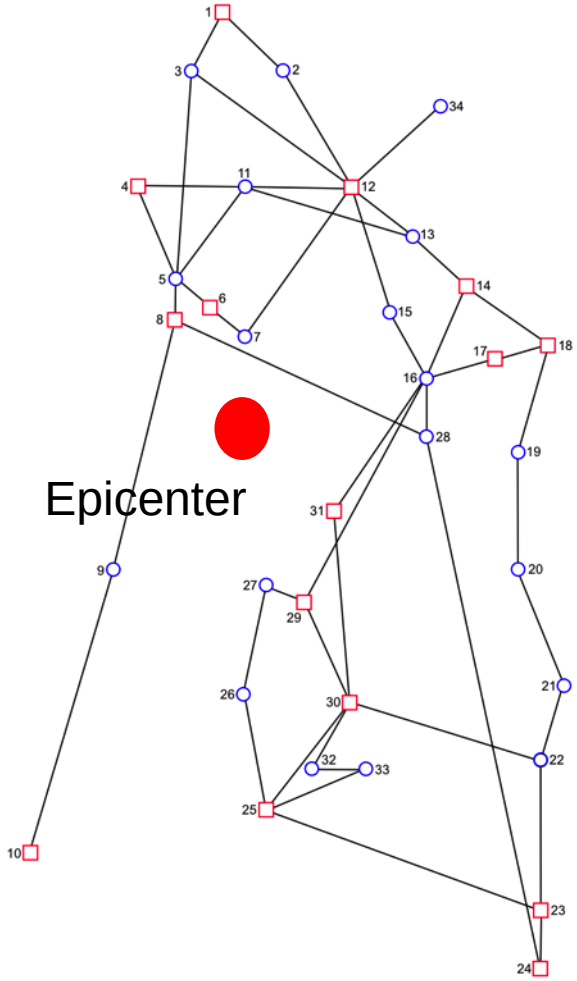
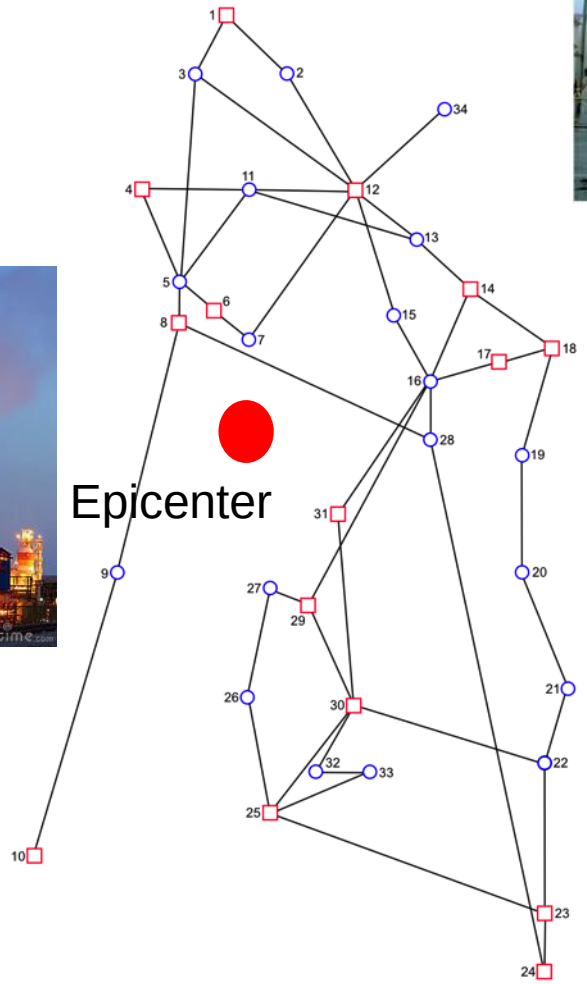
Compositional Approach: Because Damage is Local



Supply

Compositional Approach: Because Damage is Local



Demand

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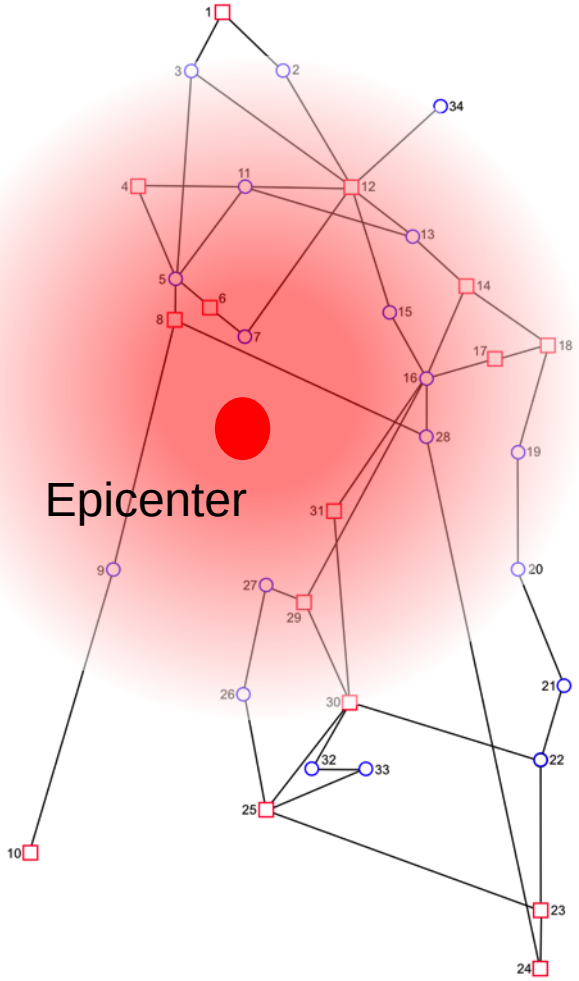
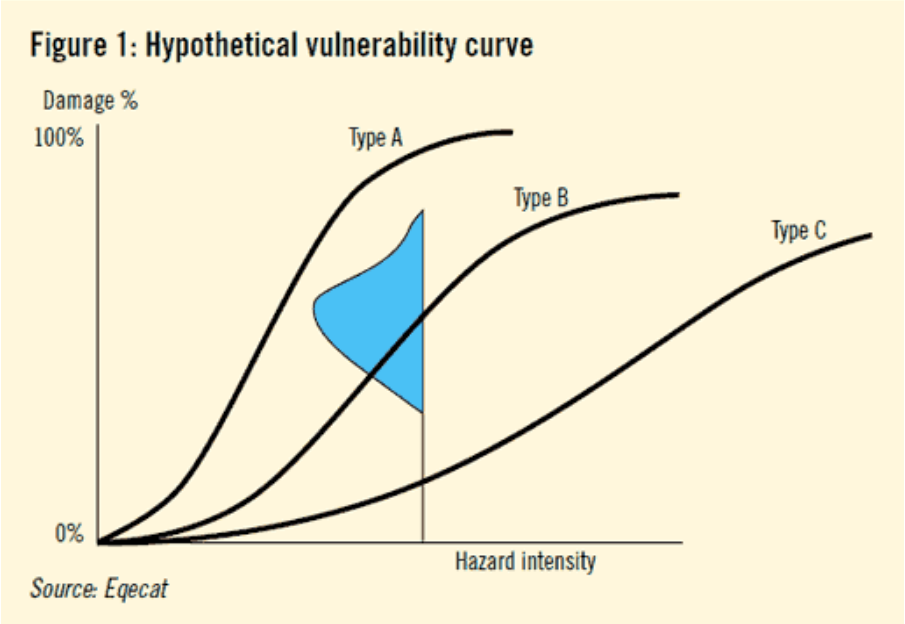
Compositional Approach: Vulnerability Functions

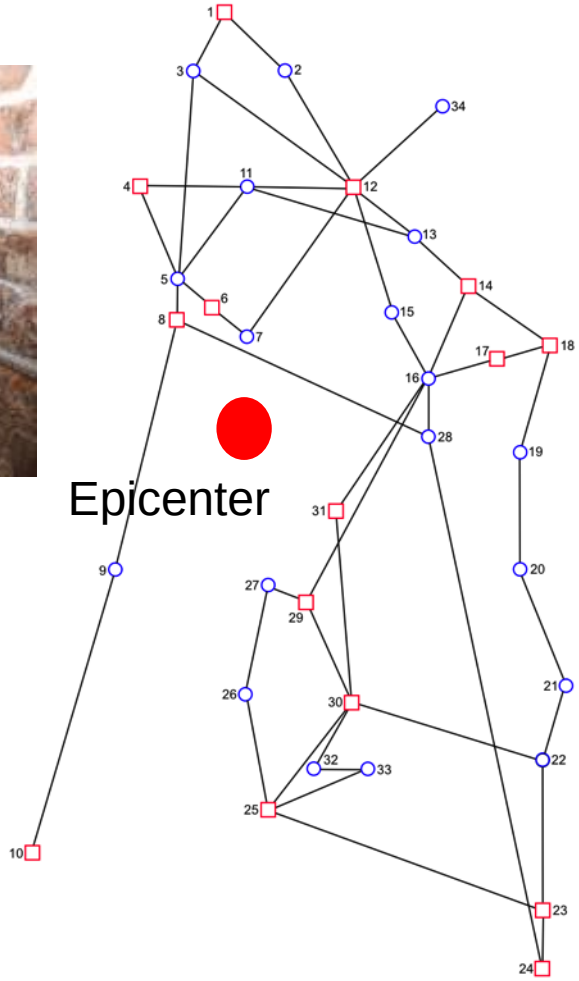


$$P(F_{Loss} > f_{loss}^{T} | IM = im)$$



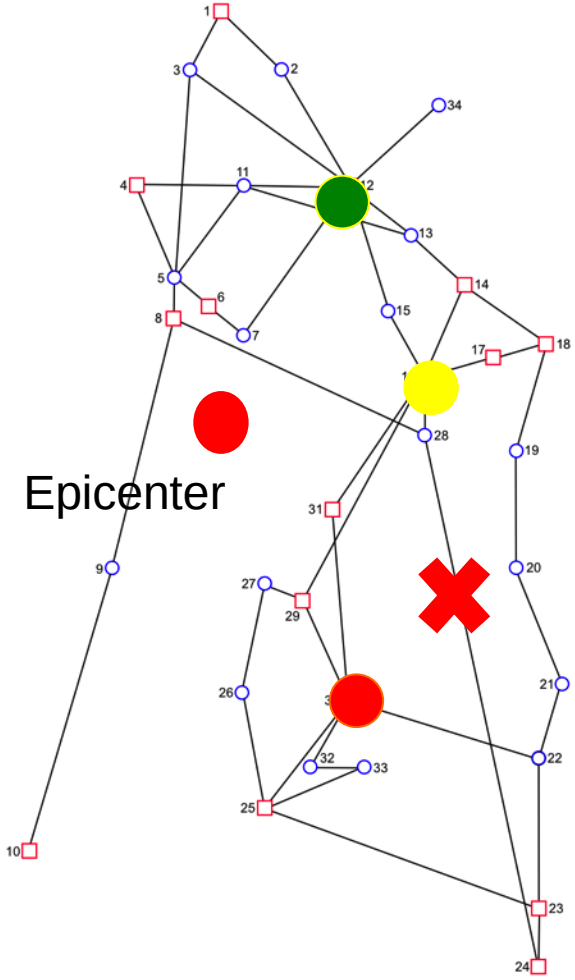
http://www.eqecat.com/blog/catastrophe-modeling/calculating-damage-earthquake-risk-models/

Compositional Approach: Because Recover is Local, too

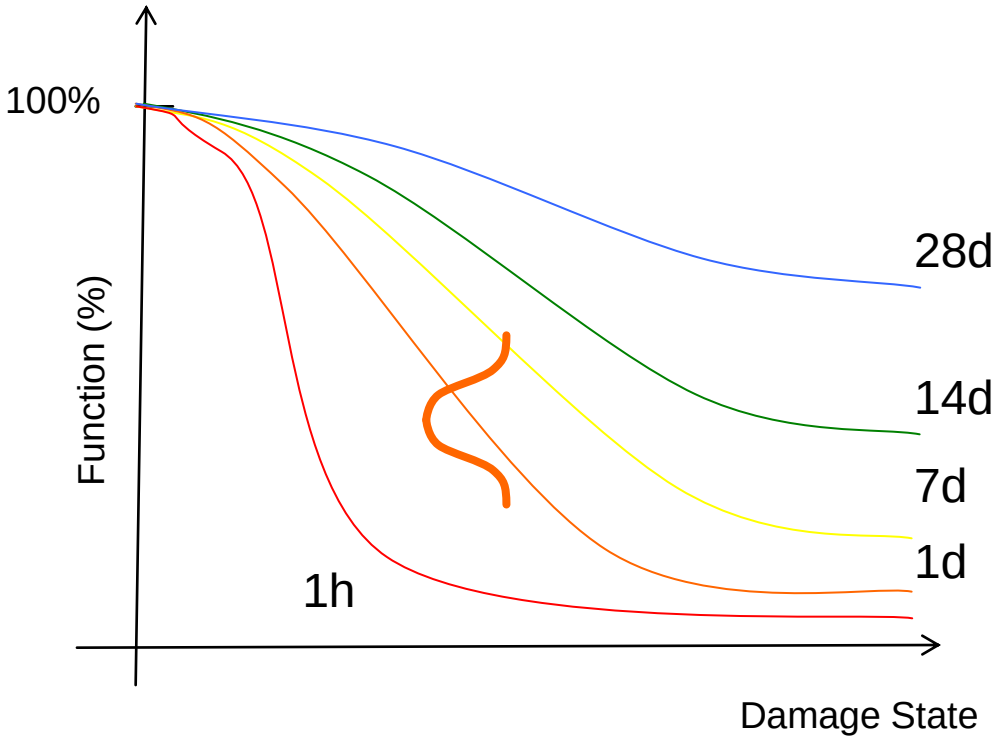


Supply & Demand

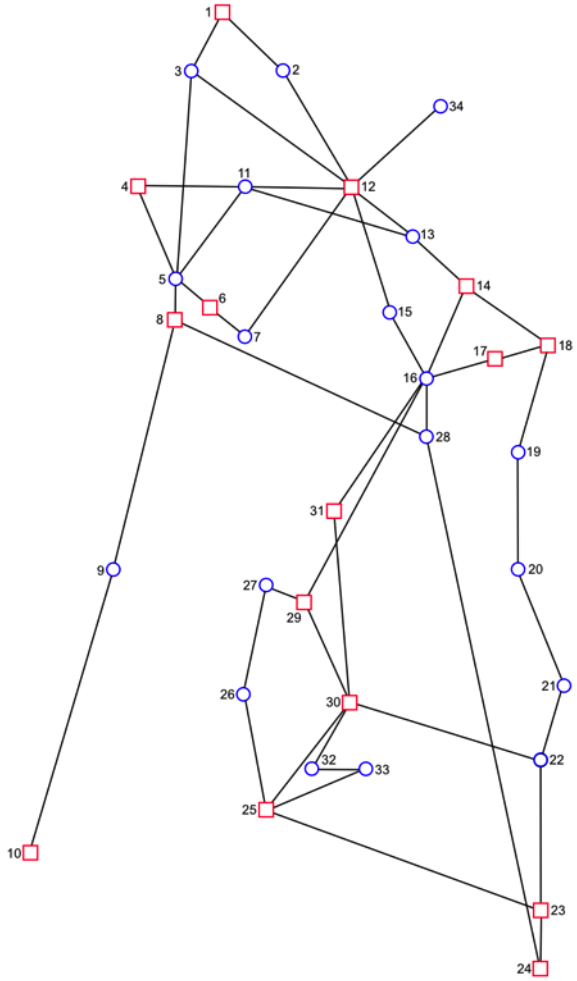
Compositional Approach: Recovery Functions

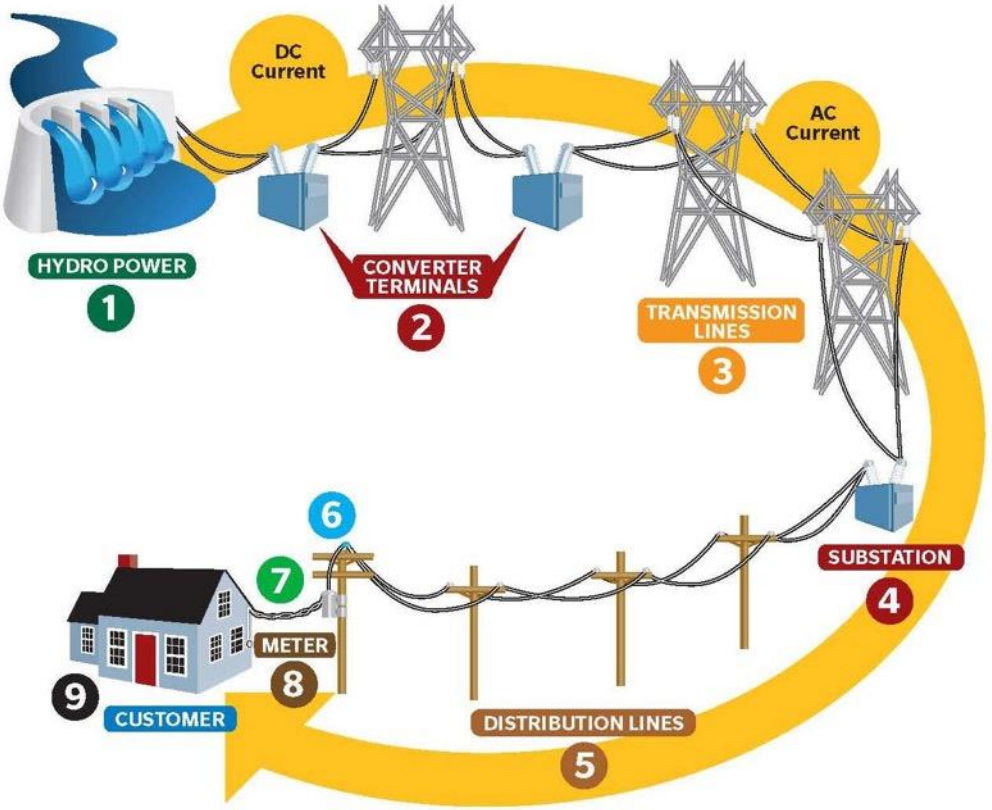


$$P(F_{Rec} > f_{rec}^{T} | DM = dm)$$



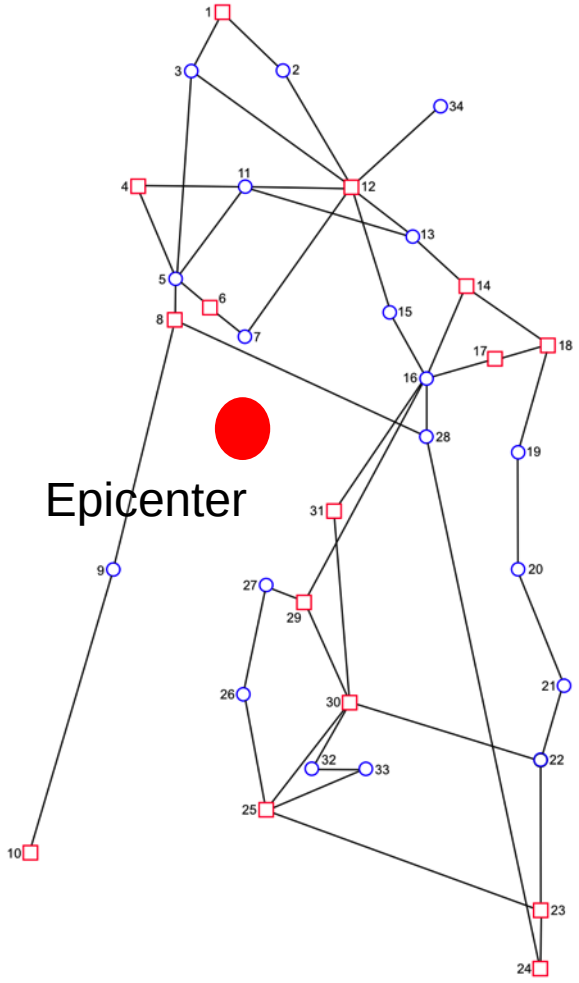
Compositional Approach: System Operation Model (Power Dispatch)

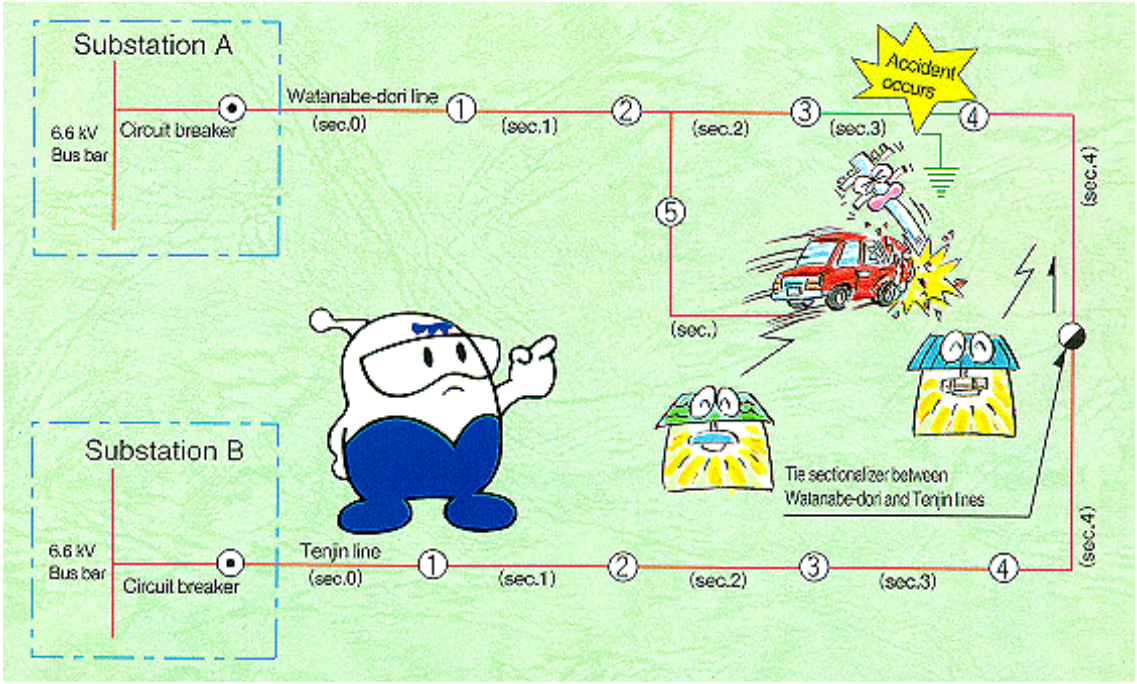




http://www.northernpass.us/regional-electric-system.htm

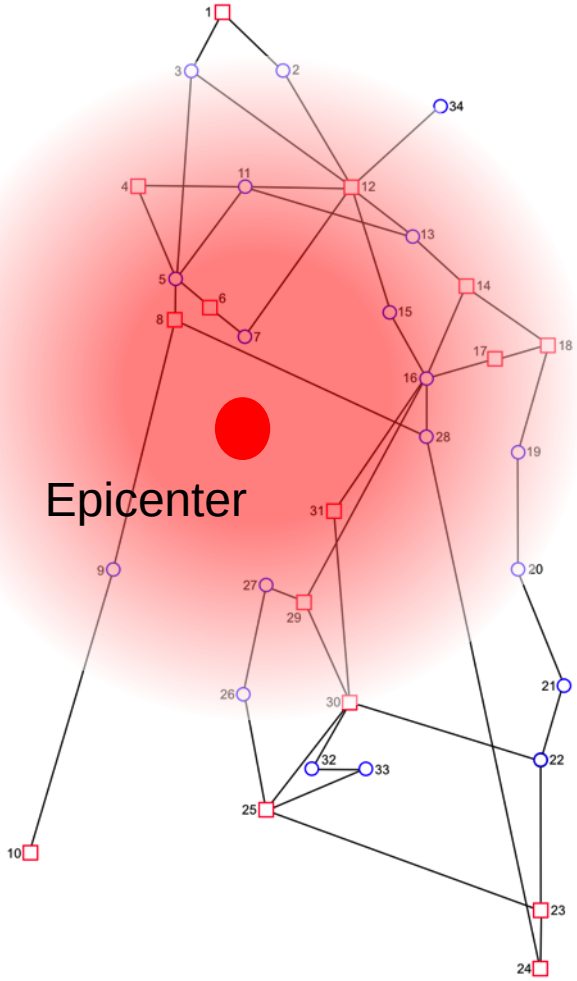
Compositional Approach: System Operation Model (Emergency Dispatch)

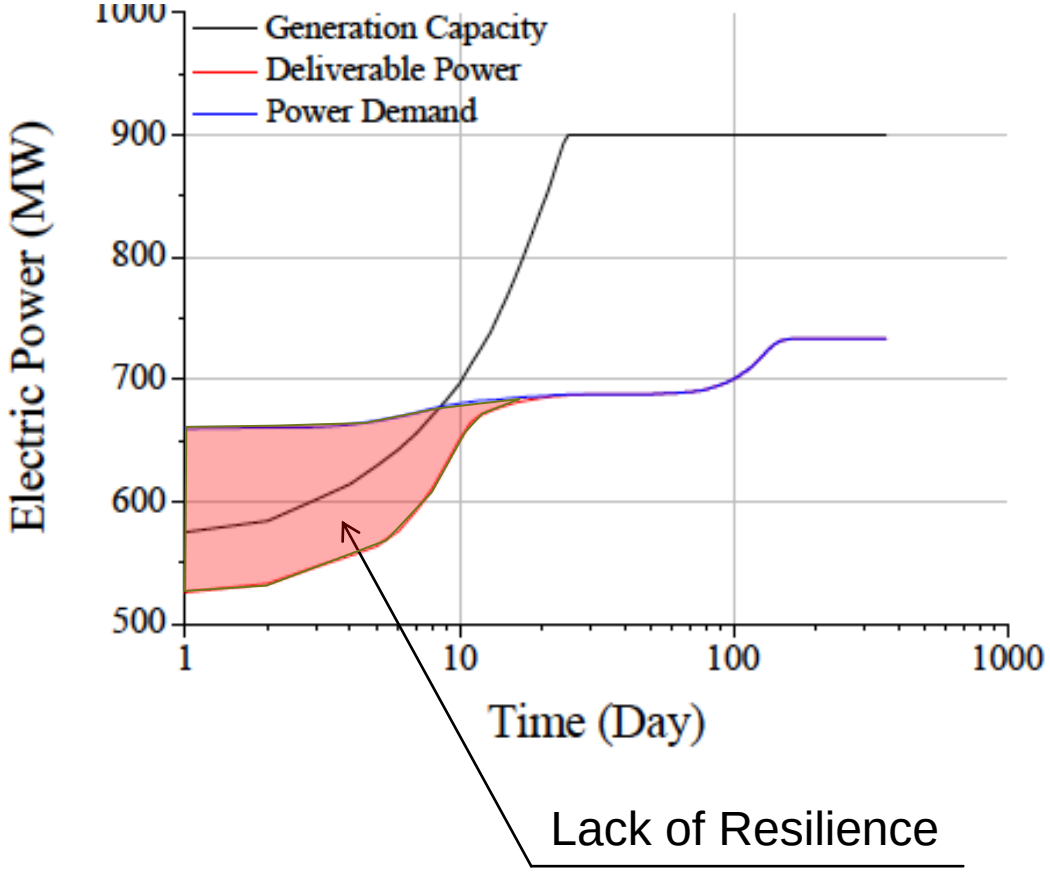




http://www.kyuden.co.jp/en_tech_distribution_introduction1

Compositional Supply/Demand Framework: Re-CoDeS





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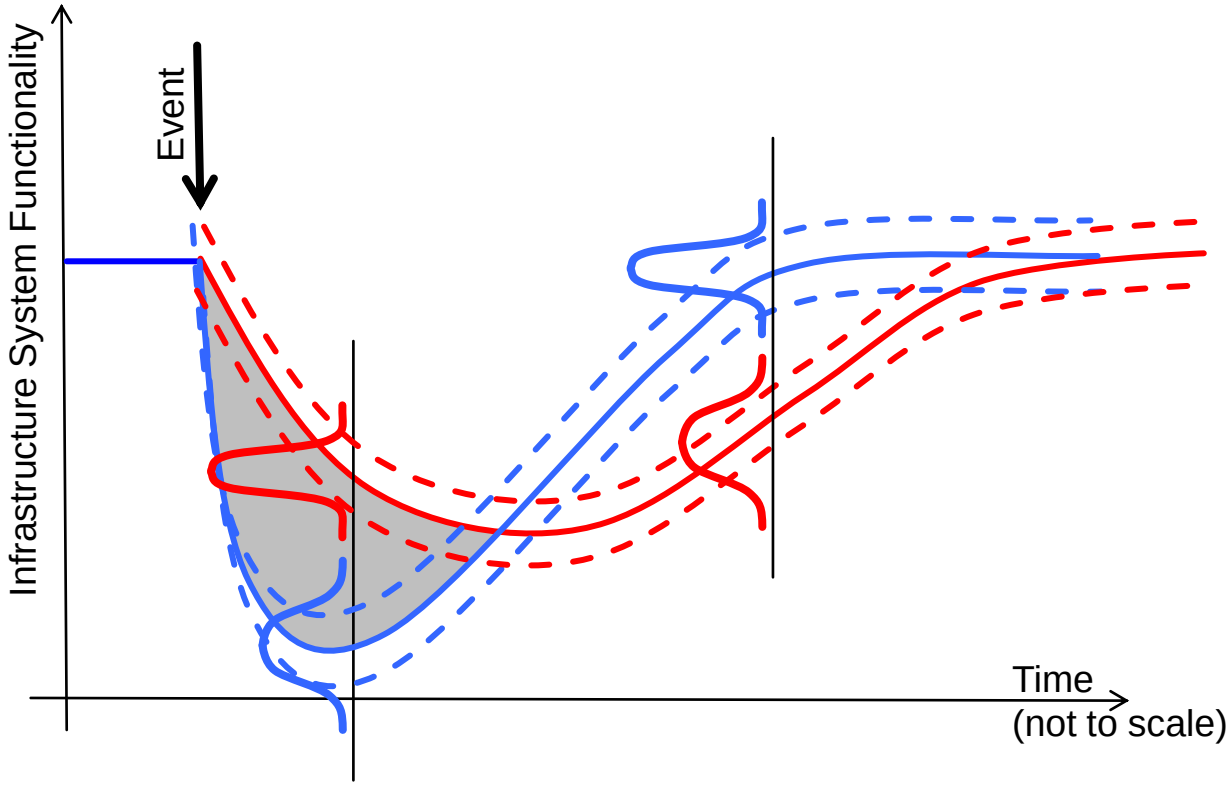
Compositional Supply/Demand Framework: Re-CoDeS

- Consider the uncertainties in:
  - Component performance
  - System performance
- (MC) simulations to characterize the probability distributions of supply and demand:
  - Median values shown



Re-CoDeS: Node Level

- Reserve margin
- Time for resilience assessment

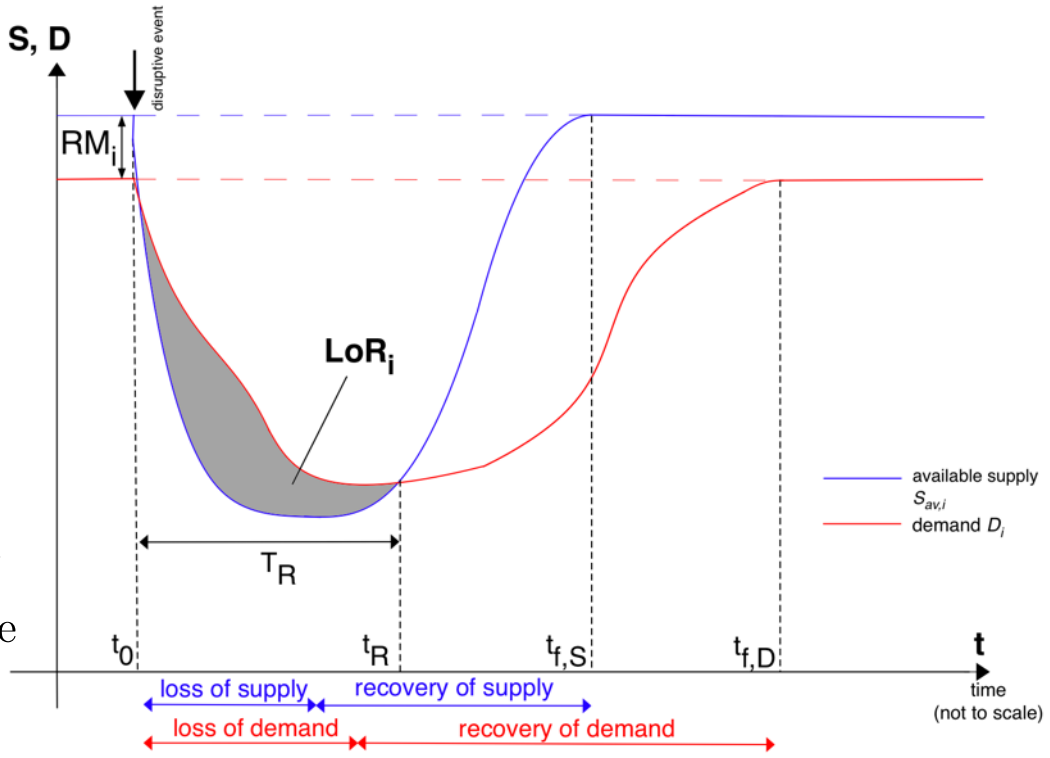
$$t \in \{t_0, t_1\}$$

- Lack of resilience is the area between the demand and the available supply curve

$$LoR_i = \int_{t_0}^{t_1} \langle D_i(t) - S_{a,i}(t) \rangle dt$$

- Singularity function

$$\langle D - S \rangle = \begin{cases} D - S & \text{if } D > S \\ 0 & \text{otherwise} \end{cases}$$



Re-CoDeS: Node Level

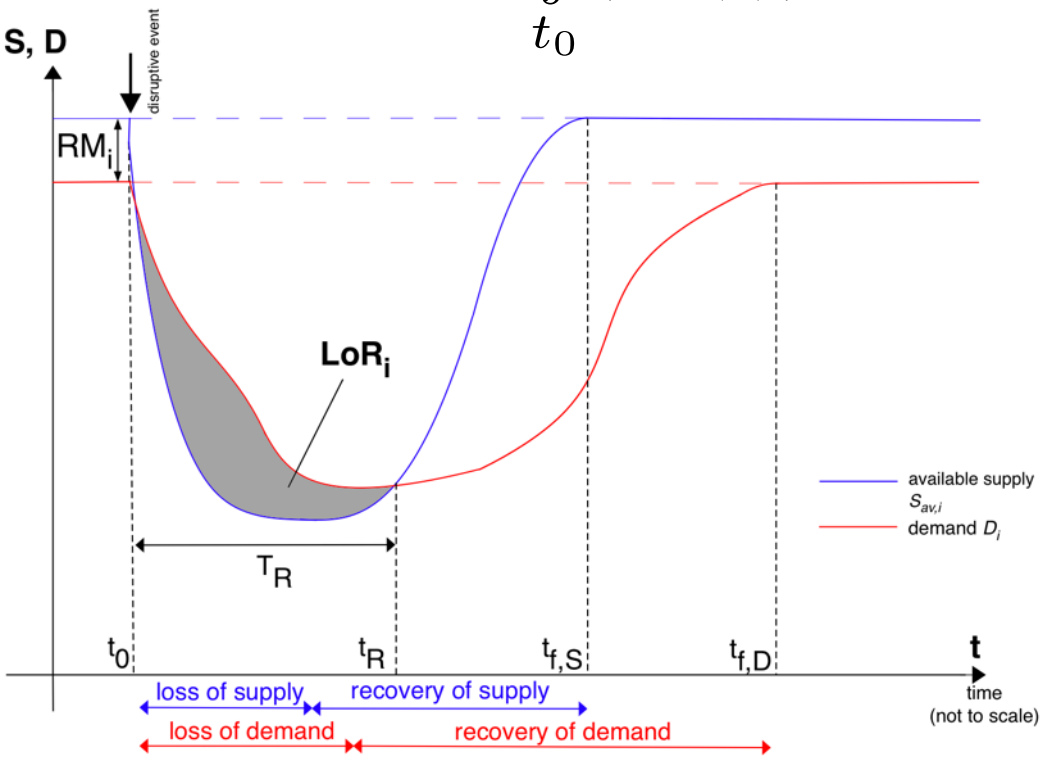
- Normalize by node demand:
  - Makes node-to-node comparison possible

$$\widehat{LoR}_i = \frac{\int_{t_0}^{t_1} \langle D_i(t) - S_{a,i}(t) \rangle dt}{\int_{t_0}^{t_1} \langle D_i(t) \rangle dt}$$

- Node Resilience

$$\hat{R}_i = 1 - \widehat{LoR}_i$$

$$\hat{R}_i \in \{0, 1\}$$



Re-CoDeS: Supply Available at a Node

- Depends on the system supply capacity and losses due to:
  - Ageing, repairs
  - Transmission
- Depends on the state of system demand

$$S_{a,i}(t) = f(\sum_{k=1}^{N}(S_{c,max,k}(t) - S_{c,loss,k}(t)), S_{c,loss,i}(t), \sum_{k=1}^{N} D_k(t) - D_i(t))$$

Re-CoDeS: System Level

- System available supply

$$S_{a,sys} \neq \sum_{i=1}^{N} S_{a,i}$$

- System Demand

$$D_{sys} = \sum_{i=1}^{N} D_i$$

- Node demand is not additive
  - Supply at nodes is correlated and depends on the operation of the system
- Node demand is additive
  - Assuming that demand at nodes is not correlated

Re-CoDeS: System Level

- Loss of resilience at the level of the system is not a simple sum of nodal loss of resilience

$$LoR_{sys} \neq \sum_{i=1}^{N} LoR_i$$

- System operation is governed by network physics, safety, and economic constraints
- EPSS dispatch:
  - Voltage balance
  - Current capacities
  - Network topology
  - Economy of baseload vs. peaking generation

$$LoR_{sys} = \bigoplus_{i=1}^{N} LoR_i$$

Re-CoDeS: Node Level

- Define node consumption as:

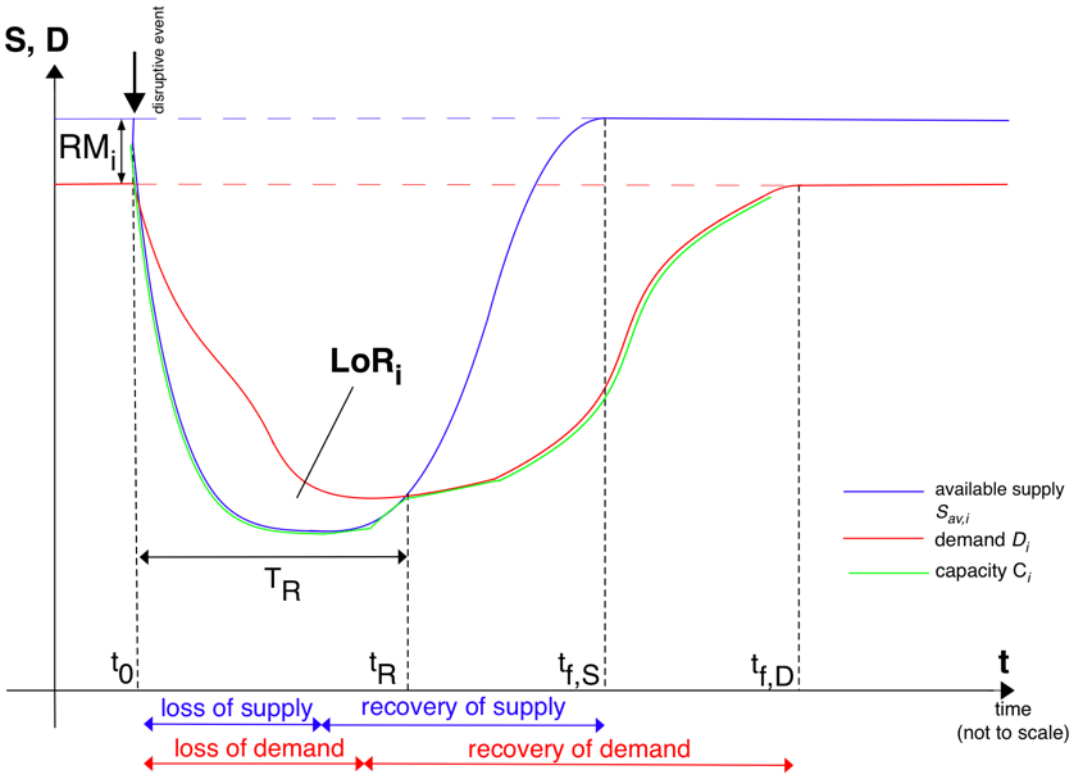
$$C_i(t) = min\{S_{a,i}(t), D_i(t)\}$$

- A node will consume as much as it can

- Node consumption is additive

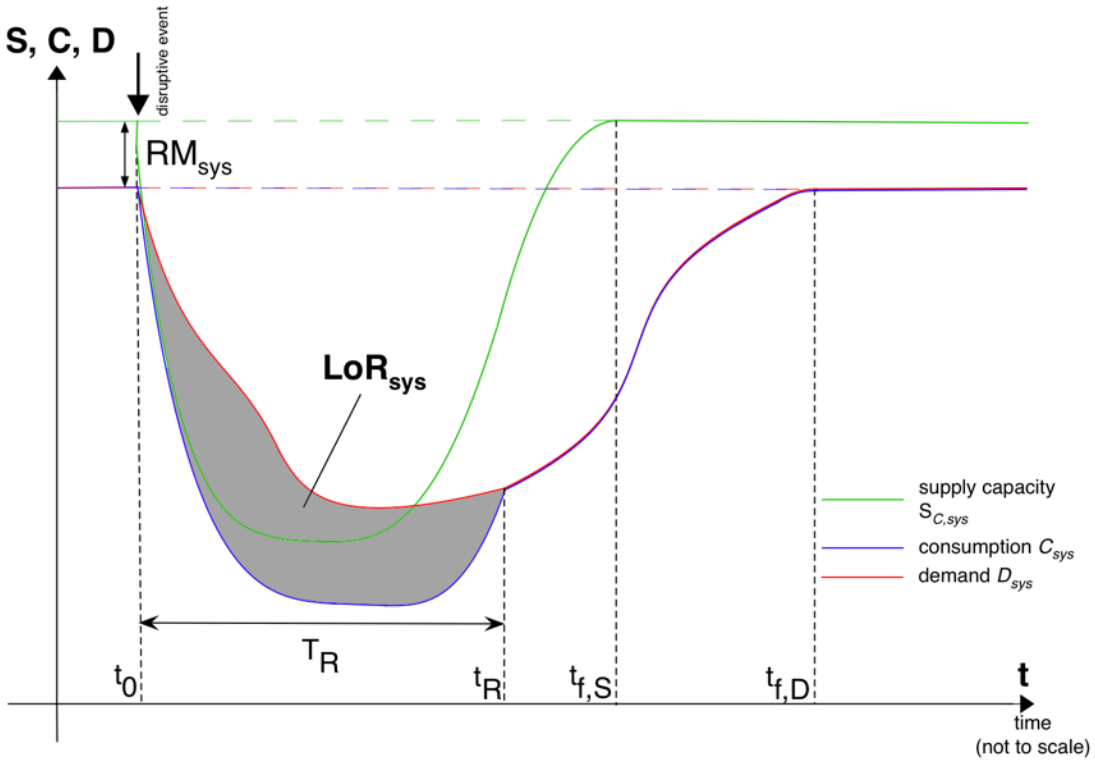
$$C_{sys} = \sum_{i=1}^{N} C_i$$

$$LoR_i = \int_{t_0}^{t_1} \{D_i(t) - C_i(t)\} dt$$



Re-CoDeS: System Level

$$LoR_{sys} = \sum_{i=1}^{N} \int_{t_0}^{t_1} \{D_i(t) - C_i(t)\} dt = \int_{t_0}^{t_1} (D_{sys}(t) - C_{sys}(t)) dt$$



Re-CoDeS: System Level

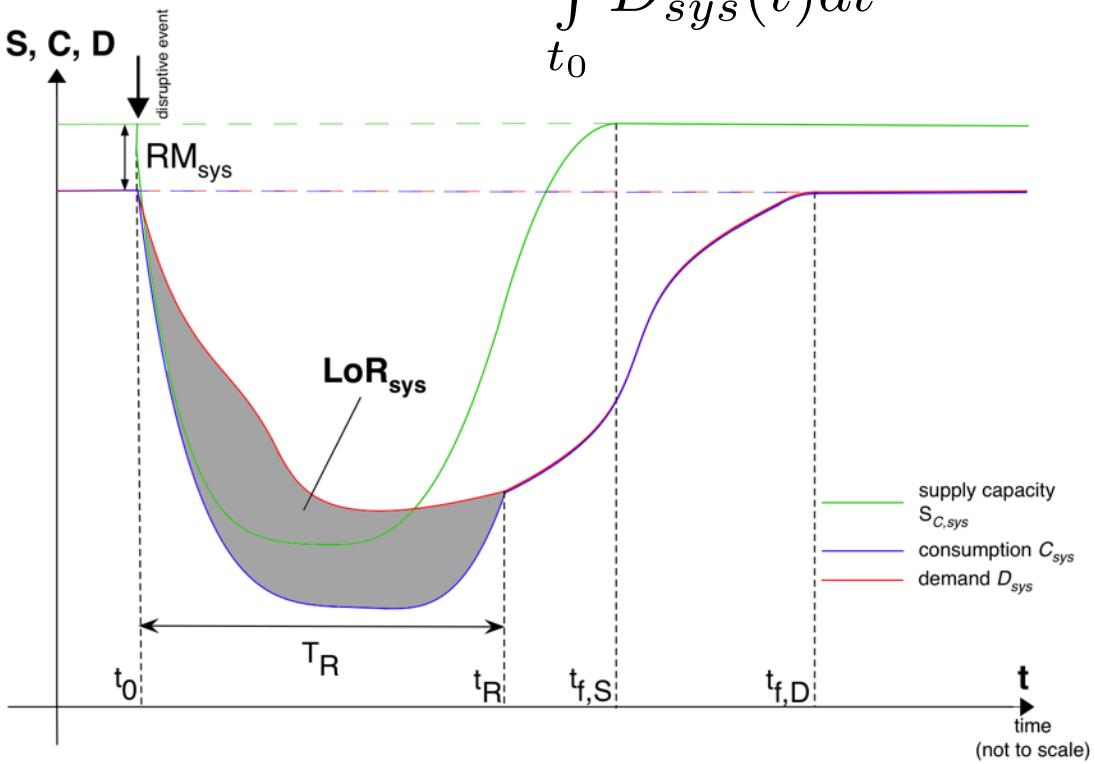
- Normalize by system demand

$$\widehat{LoR}_{sys} = \frac{\int_{t_0}^{t_1} (D_{sys}(t) - C_{sys}(t))dt}{\int_{t_0}^{t_1} D_{sys}(t)dt}$$

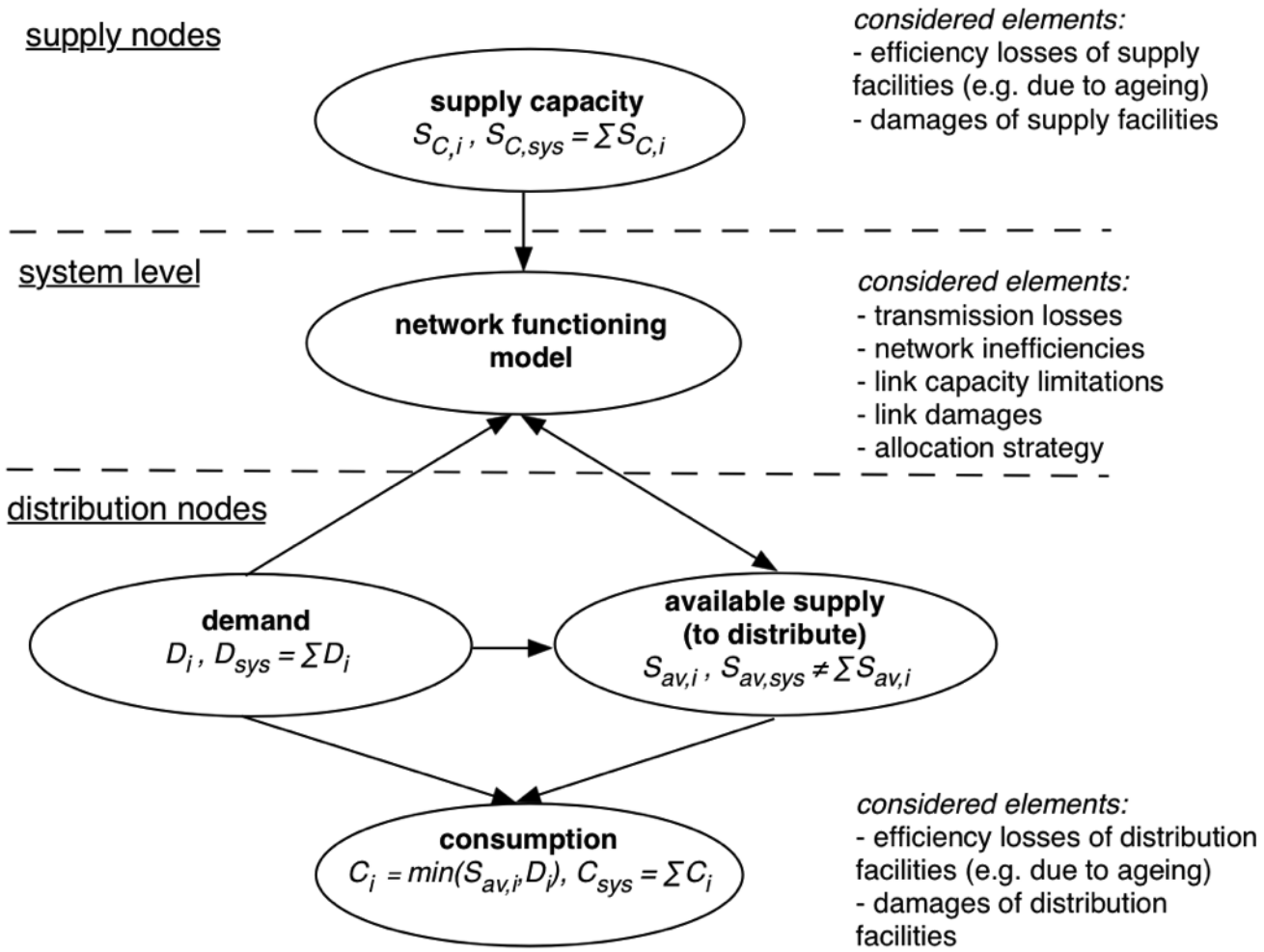
- System Resilience

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

$$\hat{R}_{sys} \in \{0, 1\}$$



Re-CoDeS Framework



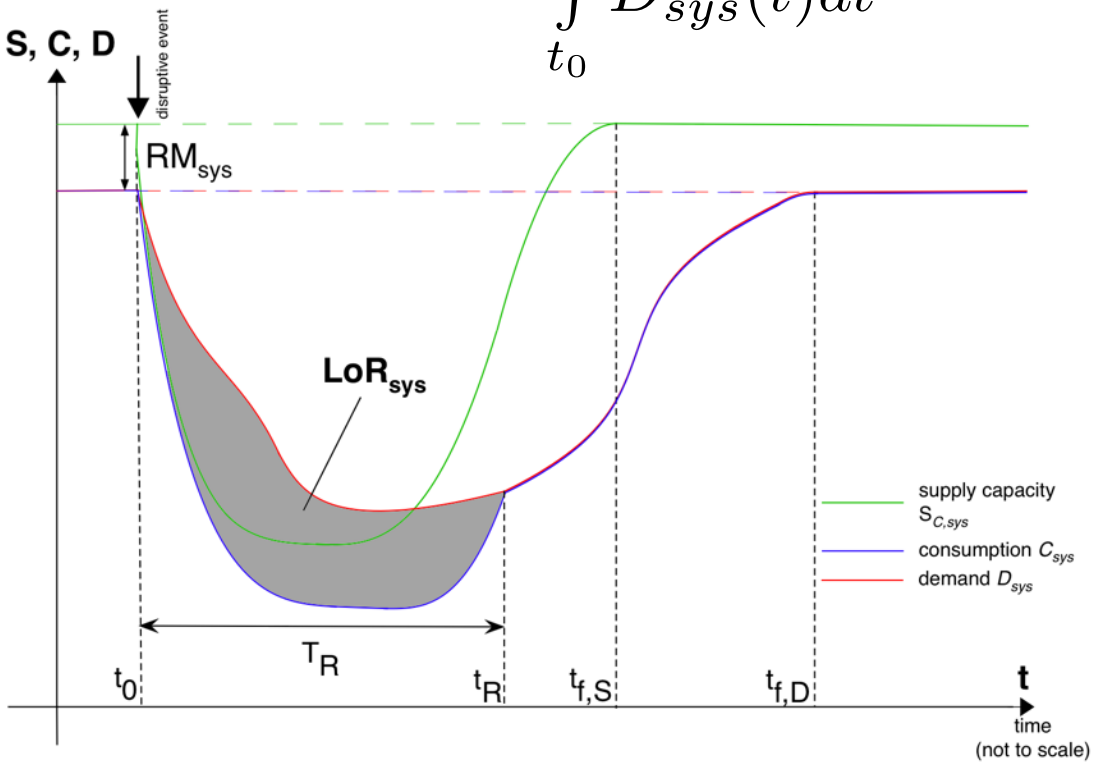
Measure of Resilience: Integral

- System Resilience

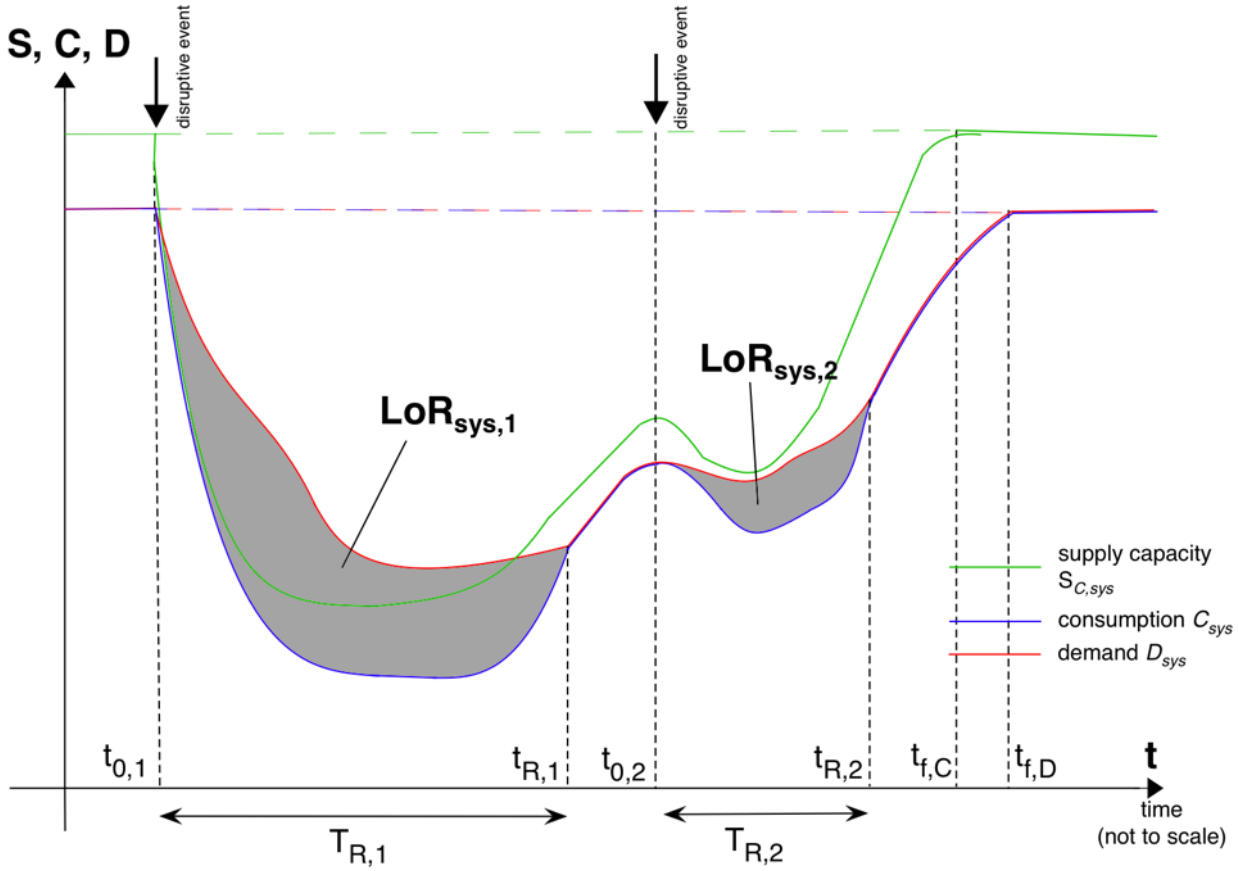
$$\hat{R}_{sys} = 1 - \widehat{LoR}_{sys}$$

$$\hat{R}_{sys} \in \{0, 1\}$$

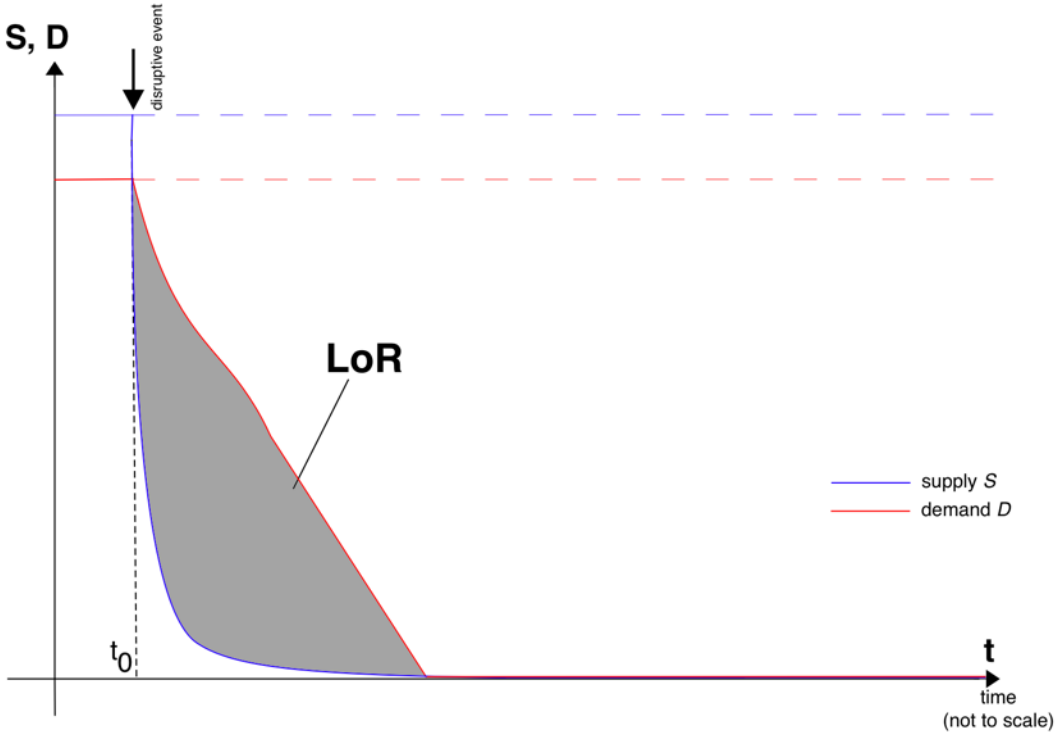
$$\widehat{LoR}_{sys} = \frac{\int_{t_0}^{t_1} (D_{sys}(t) - C_{sys}(t))dt}{\int_{t_0}^{t_1} D_{sys}(t)dt}$$

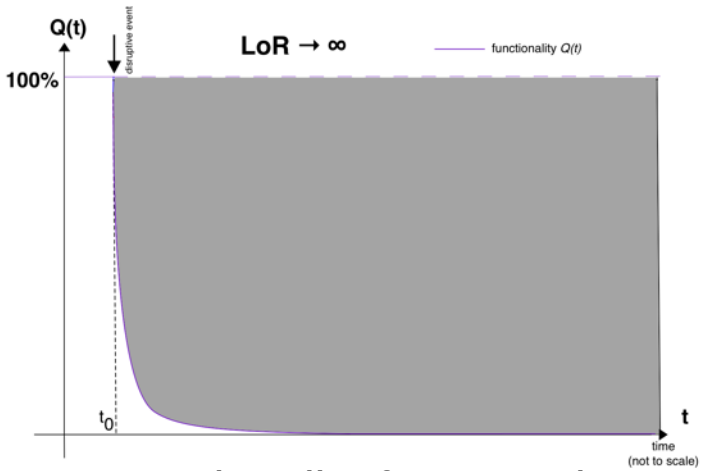


Integral Measure of Resilience: Repeated Lack of Resilience Scenario



Integral Measure of Resilience: “Pompeii” Scenario





Functionality framework

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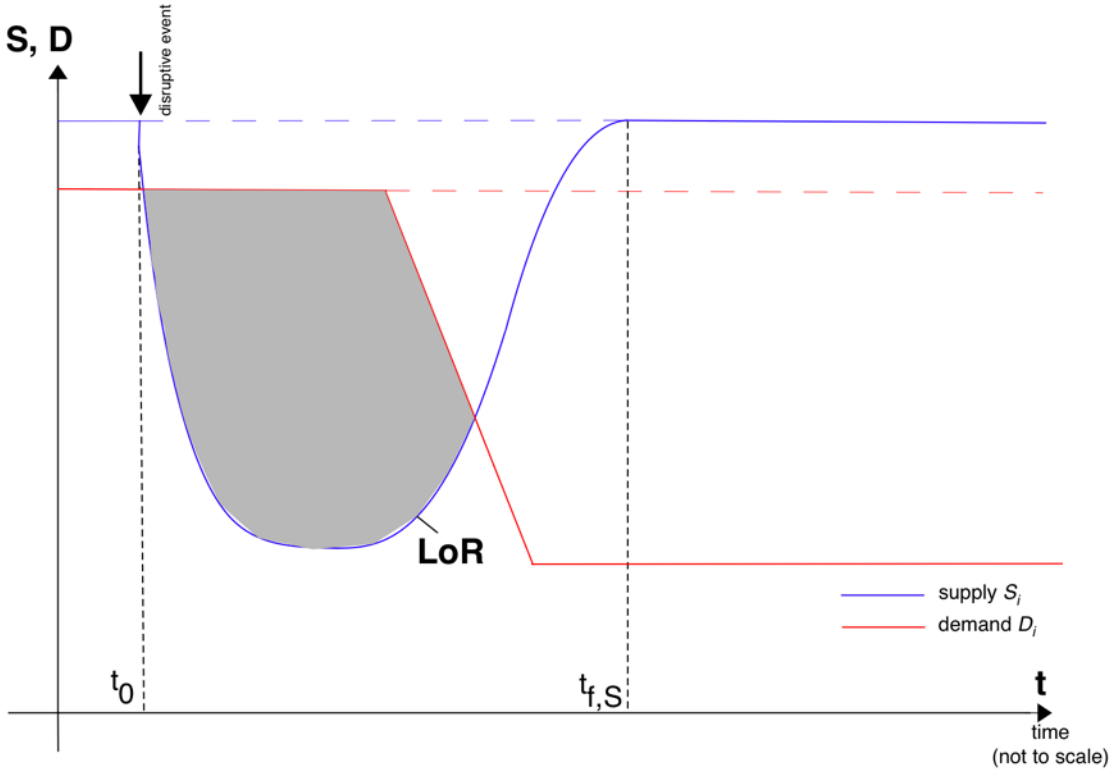
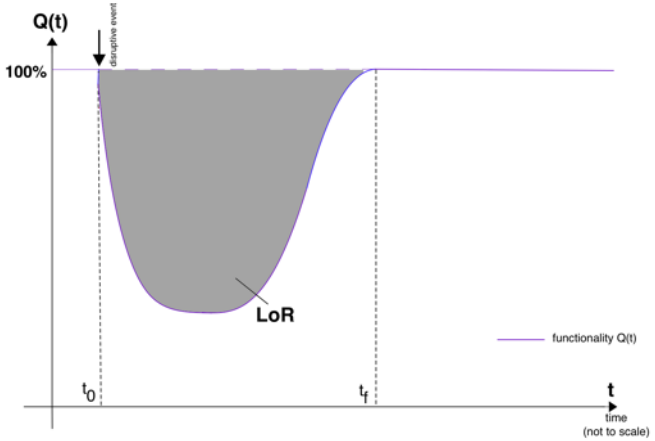
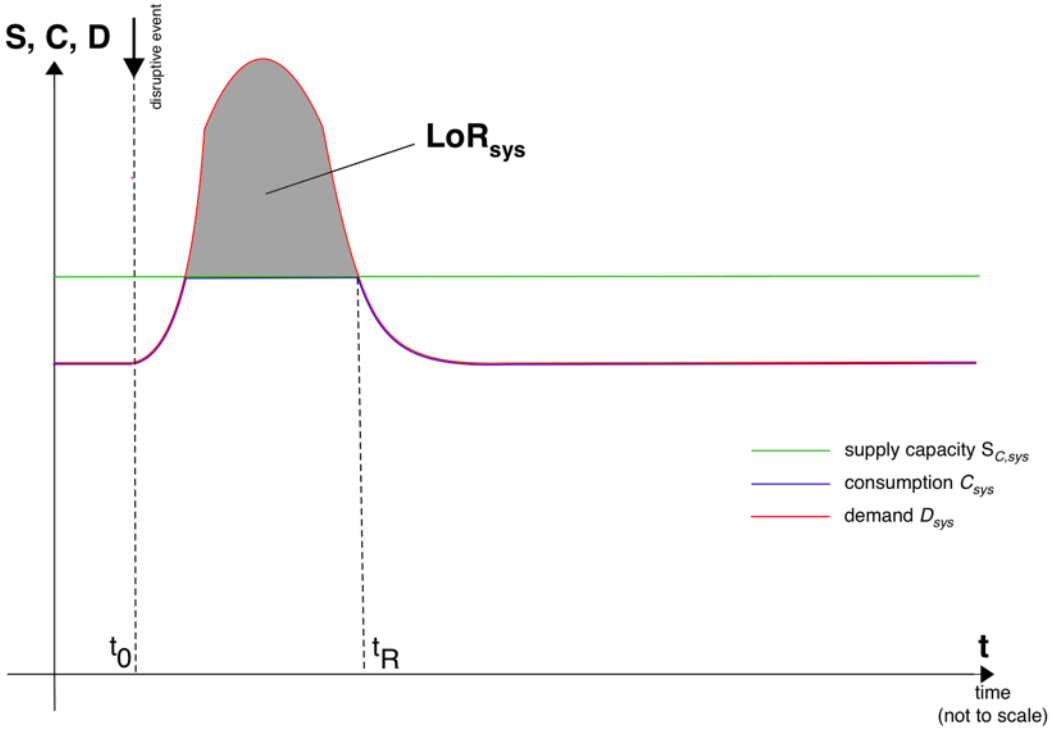
Integral Measure of Resilience: "Port of Kobe" Scenario

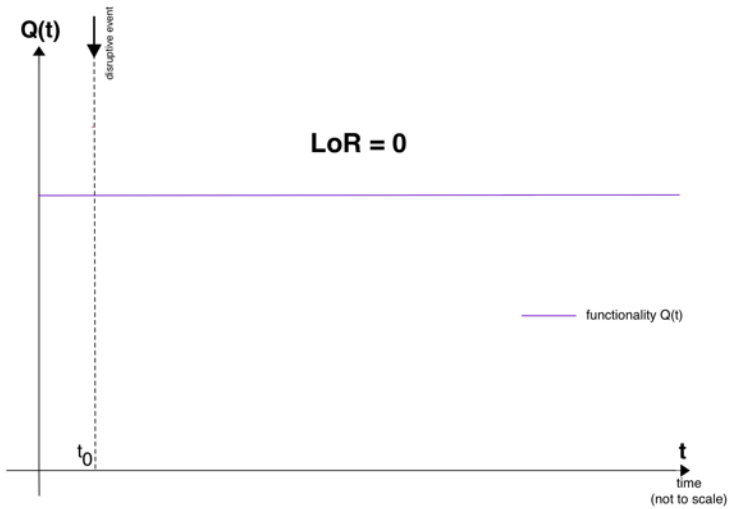




Functionality framework

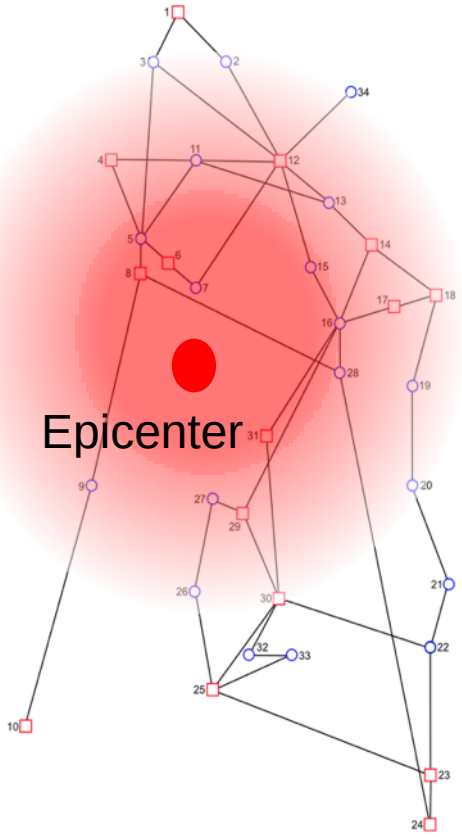
Integral Measure of Resilience: Cellular Network Example



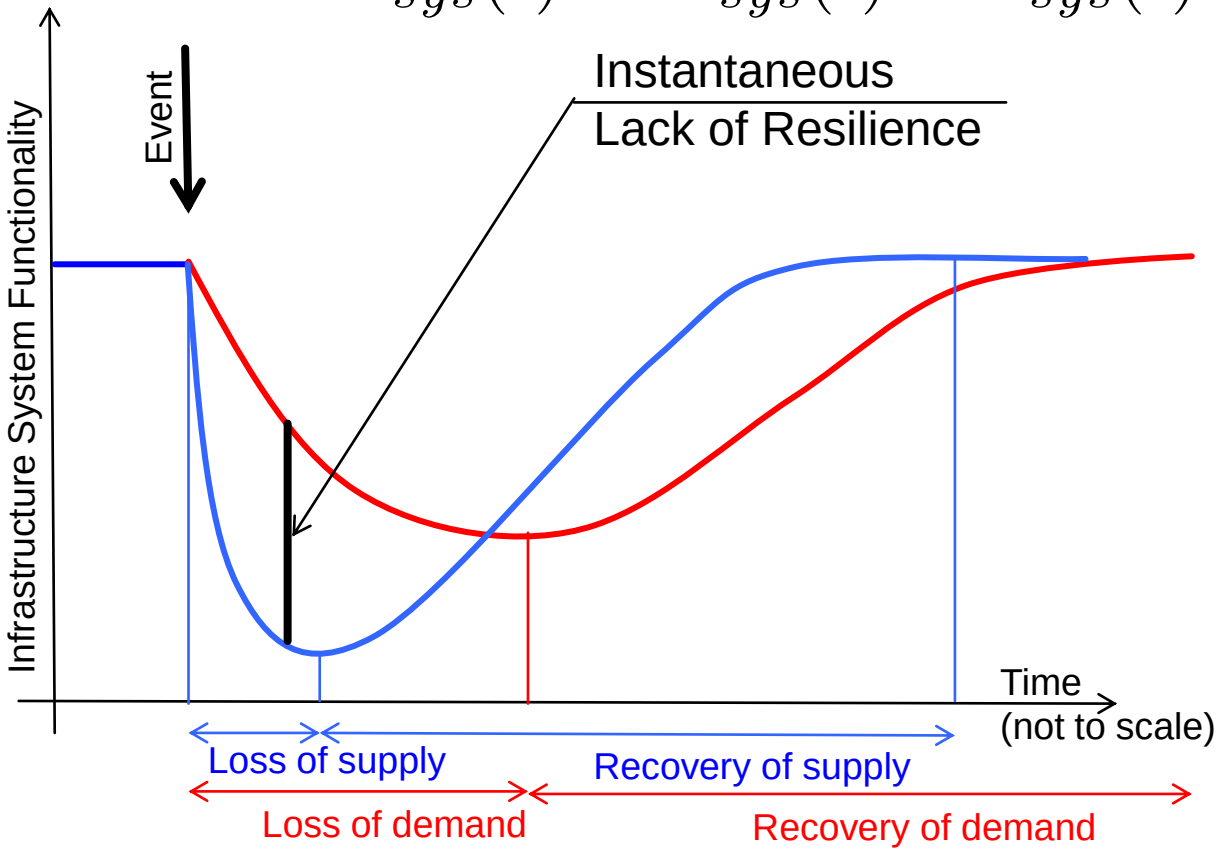


Functionality framework

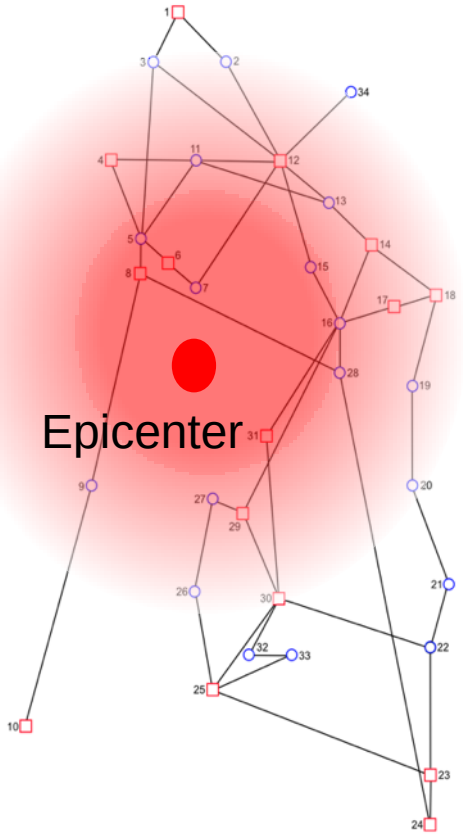
Measure of Resilience: Instantaneous



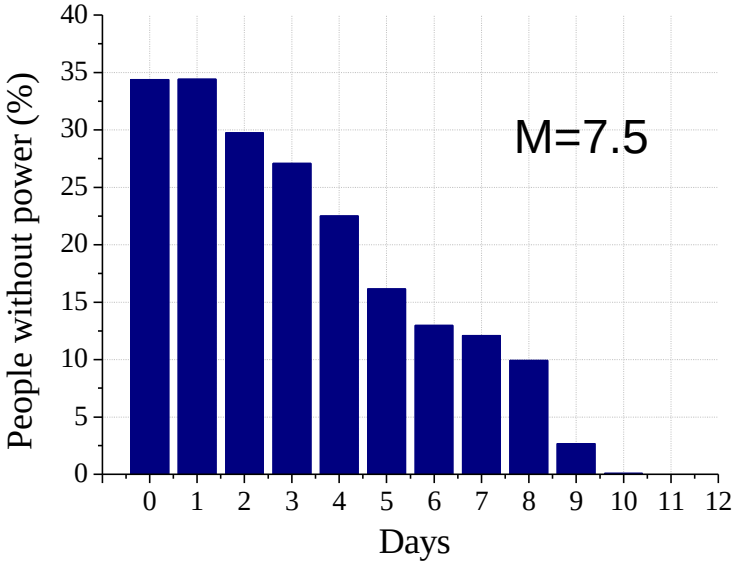
$$LoR_{sys}(t) = D_{sys}(t) - C_{sys}(t)$$

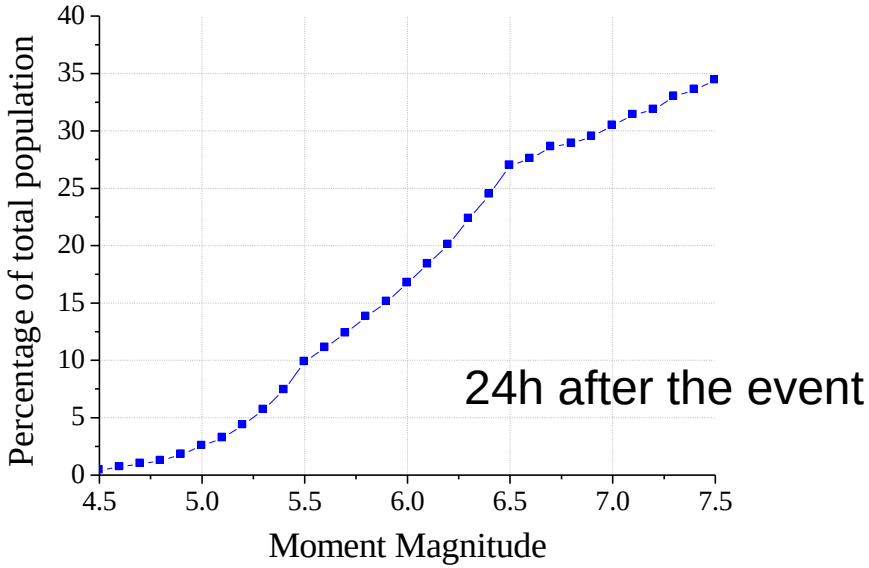


Measure of Resilience: Instantaneous



Percentage of people w/o power





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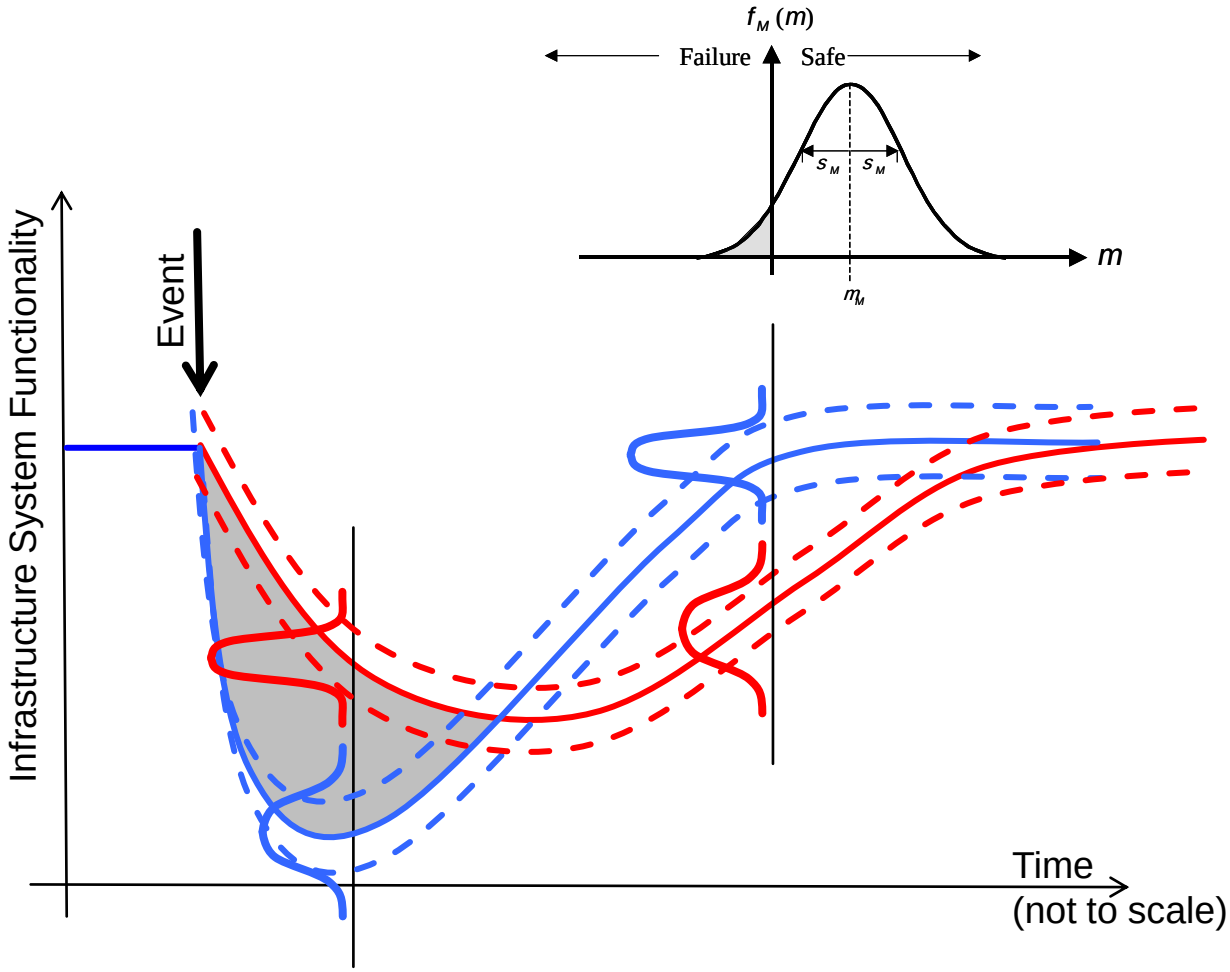
Measure of Resilience: Probabilistic Formulation

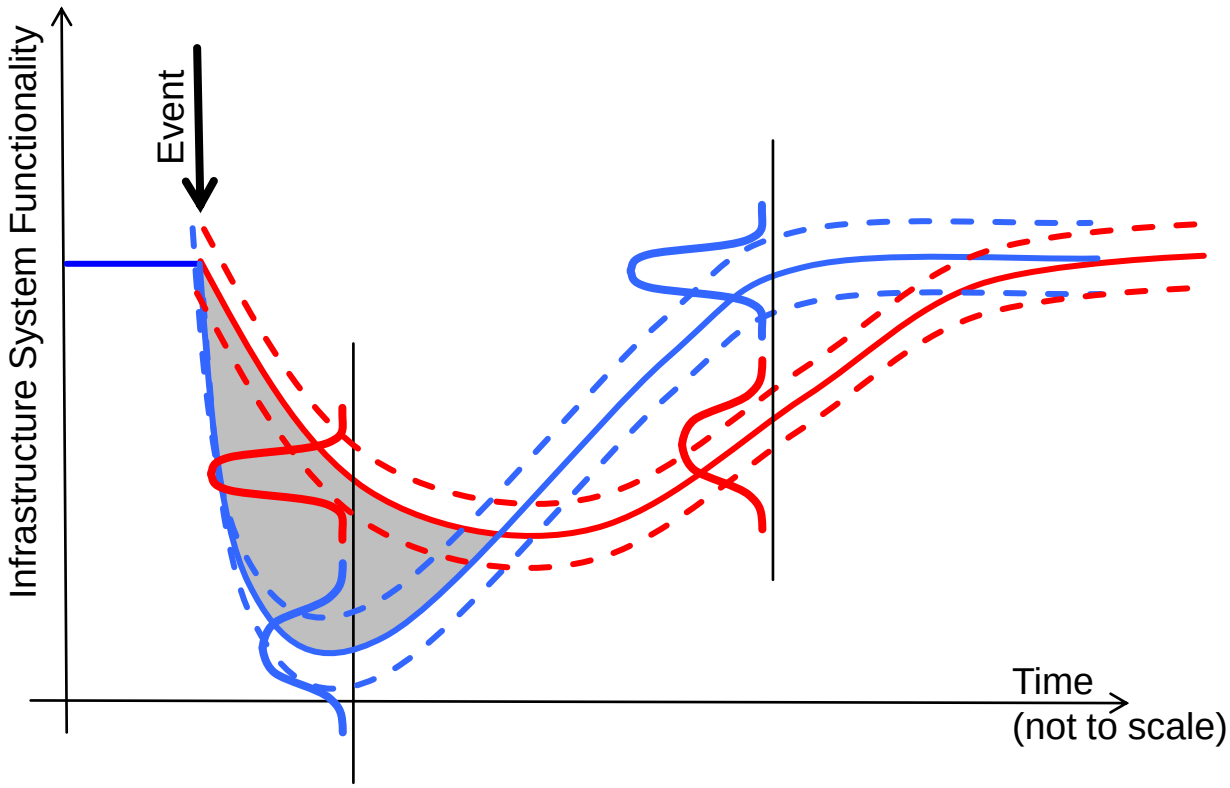
- Consider the uncertainty in demand and in supply
- Estimate the probability of LoR exceeding an acceptable threshold
  - Confidence in resilience estimates



Re-CoDeS: Resilience Acceptance Criteria

- Evaluate the probability that system resilience will be below an acceptable threshold given:
  - The hazard environment
  - The vulnerability
    - Robustness
    - Redundancy
  - The capability to recover
    - Resourcefulness
    - Rapidity

$$P(\hat{R}_{sys} < \hat{r}_{sys} | [h, v, r])$$

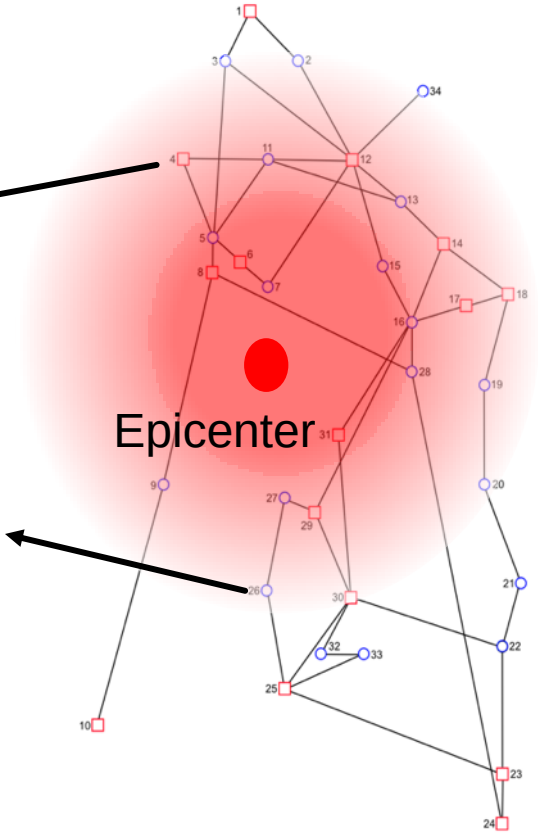


Engineering Community Resilience

- Acceptance criteria are at the system level

$$P(\hat{R}_{sys} < \hat{r}_{sys} | [h, v, r])$$

(a)

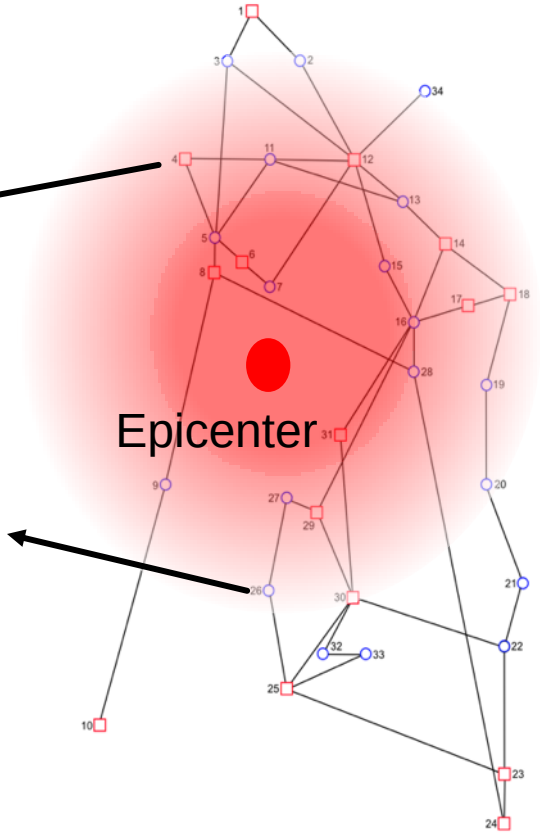


Engineering Community Resilience

- An engineer designs a node of the system, one node at a time
- System-level acceptance criteria must be de-convolved to the node (component) level

$$P(\hat{R}_{sys} < \hat{r}_{sys} | [h, v, r])$$

(a)



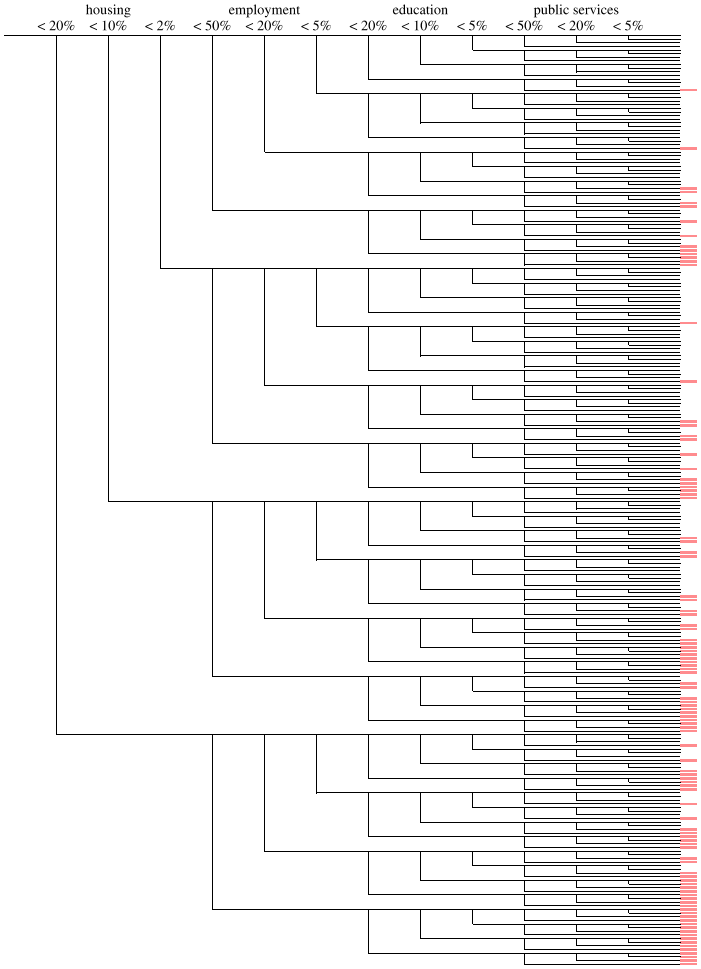
De-Convolution of Resilience Acceptance Criteria: From Community to Components

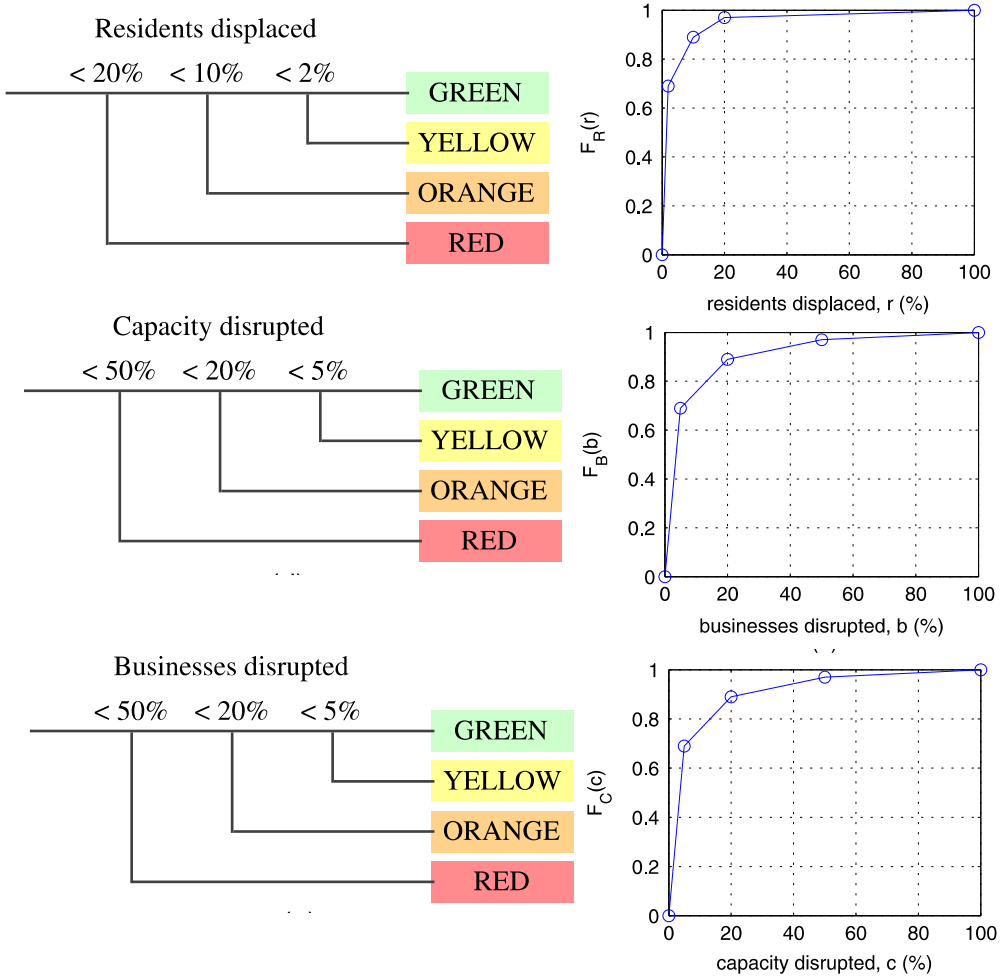
- **Stakeholder perspective:**
  - Acceptable initial loss
    - Operational
    - Monetary
  - Acceptable recovery tempo
    - Operational
    - Monetary
- **Societal perspective:**
  - Acceptable initial loss
    - Economic
    - Environmental
  - Acceptable recovery tempo
    - Economic
    - Environmental

Functional Category: Cluster	(4) Support Needed	Overall Recovery Time for Hazard and Level Listed Expected Hazard Level								
		Phase 1 – Short-Term			Phase 2 – Intermediate			Phase 3 – Long-Term		
		Days			Wks			Mos		
		0	1	1-3	1-4	4-8	8-12	4	4-24	24+
Power - Electric Utilities										
Bulk Generation										
Renewable, Non-Variable (Hydro, Biomass, Geothermal, Pump Storage)	R/C	90%	X							
Transmission (including Substations)										
Critical Response Facilities and Support Systems										
Hospitals, Police and Fire Stations / Emergency Operations Centers	R, C	90%	X							
Disaster debris / recycling centers/ related lifeline systems	R, C	60%	90%	X						
Emergency Housing and Support Systems										
Public Shelters / Nursing Homes / Food Distribution Centers	R, C	60%	90%	X						
Emergency shelter for response / recovery workforce/ Key Commercial and Finance	R, C		60%	90%	X					
Housing and Neighborhood infrastructure										
Essential city services / schools / Medical offices	R, C		60%	90%	X					
Houses of worship/meditation/ exercise	C		60%	90%	X					
Buildings/space for social services (e.g., child services) and prosecution activities	C		60%	90%	X					
Community Recovery Infrastructure										
Commercial and industrial businesses / Non-emergency city services	C			60%	90%	X				
Residential housing restoration	R, S, MS, C			60%	90%	X				
Distribution										
Critical Response Facilities and Support Systems										
Hospitals, Police and Fire Stations / Emergency Operations Centers	R, C	60%	90%	X						
Disaster debris / recycling centers/ related lifeline systems	R, C	60%	90%	X						
Emergency Housing and Support Systems										
Public Shelters / Nursing Homes / Food Distribution Centers	R, C		60%	90%	X					
Emergency shelter for response / recovery workforce/ Key Commercial and Finance	R, C		60%	90%	X					
Housing and Neighborhood infrastructure										
Essential city services / schools / Medical offices	R, C		60%	90%	X					
Houses of worship/meditation/ exercise	C		60%	90%	X					
Buildings/space for social services (e.g., child services) and prosecution activities	C		60%	90%	X					
Community Recovery Infrastructure										
Commercial and industrial businesses / Non-emergency city services	C			90%	X					
Residential housing restoration	R, S, MS, C			90%	X					

NIST SP-1190 “Community Resilience Planning Guide for Buildings and Infrastructure Systems”

De-Convolution of Resilience Acceptance Criteria: From Community Outmigration to Component Robustness





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Mieler, M., B. Stojadinovic, R. Budnitz, M. Comerio and S. Mahin, “A Framework for Linking Community-Resilience Goals to Specific Performance Targets for the Built Environment”, Earthquake Spectra, vol. 31, no. 3, pp. 1267-1283, August 2015.

De-Convolution of Resilience Acceptance Criteria: From Community Outmigration to Component Robustness

Entity	Performance objective
Community	<1% probability of significant outmigration
Vital functions	*Housing*: <5% of residents displaced *Employment*: <9% of businesses disrupted *Education*: <6% of students displaced *Public services*: <9% of capacity disrupted
Housing stock	<5% of residential buildings unsafe to occupy
Individual residential buildings	<5% probability of being unsafe to occupy

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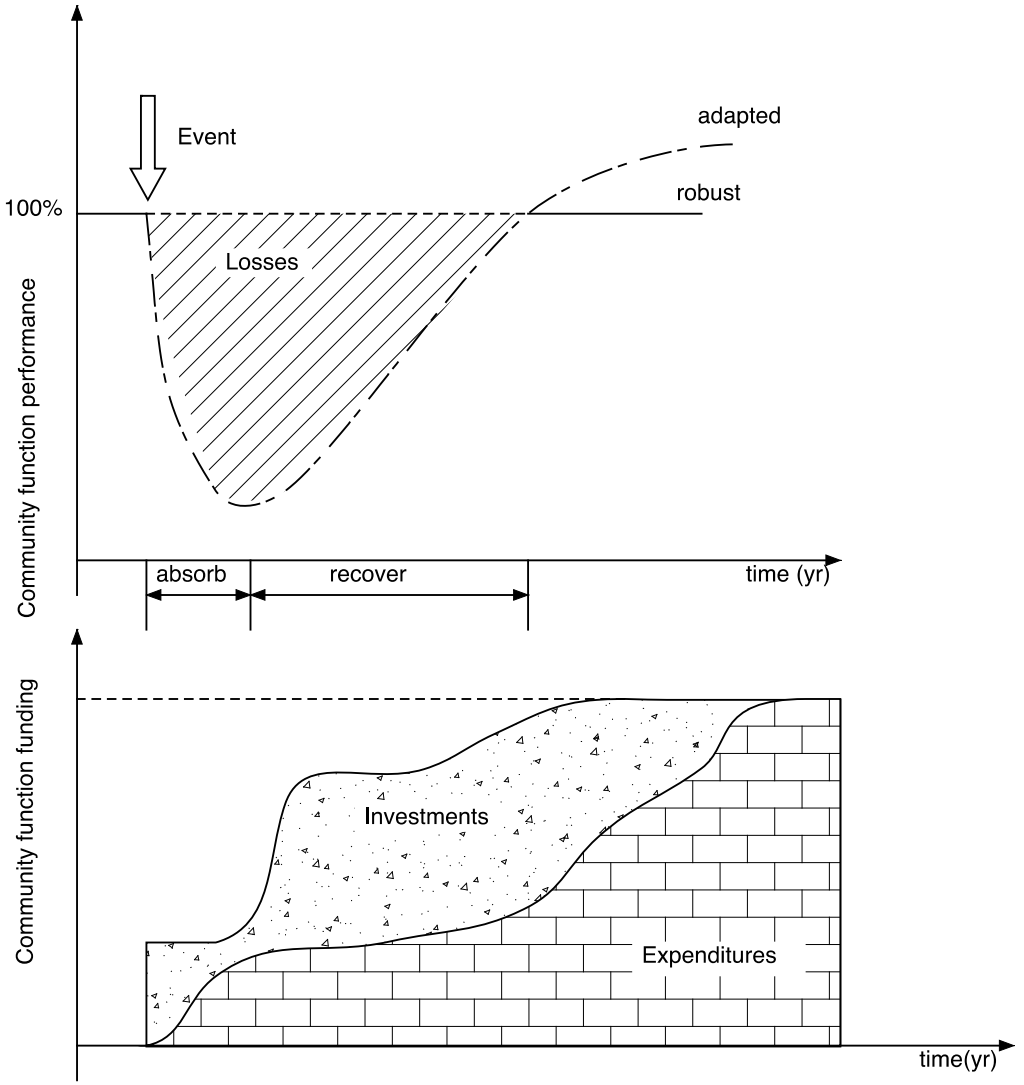
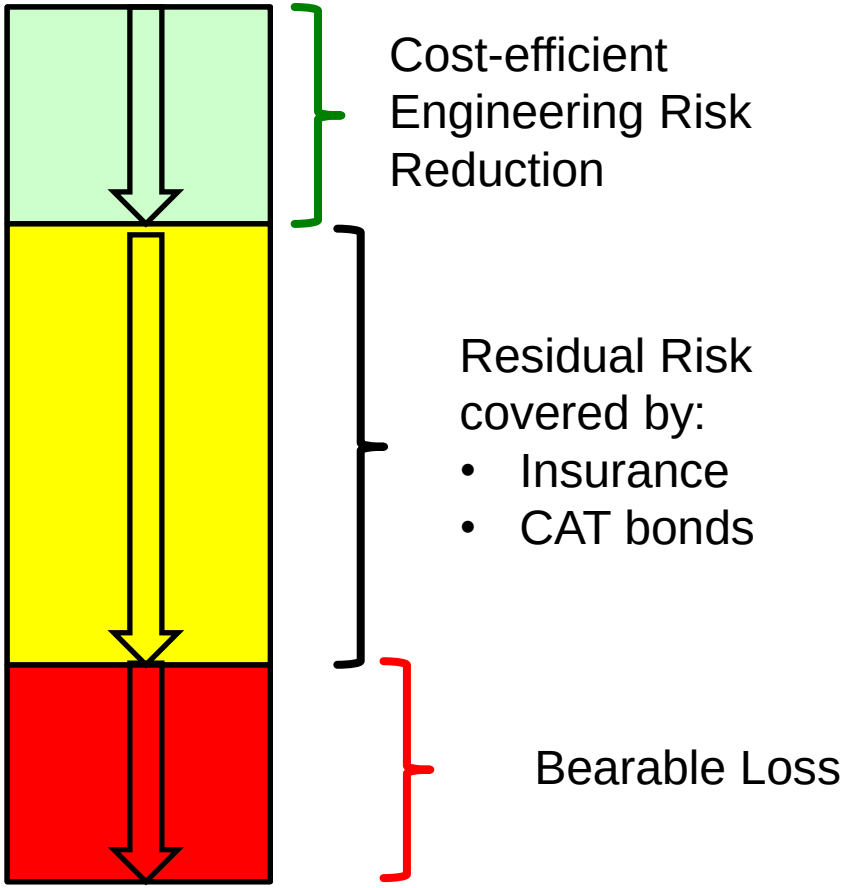
Engineering Community Resilience: Structural, Financial, Public Policies

- Resilience-based design is not only about robust new construction
- It is also about:
  - Retrofit of existing structures
  - Effective recovery of disrupted services and repair of incurred damage
- Investments drive the recovery process and community resilience decisions



Engineering Community Resilience: Structural, Financial, Public Policies

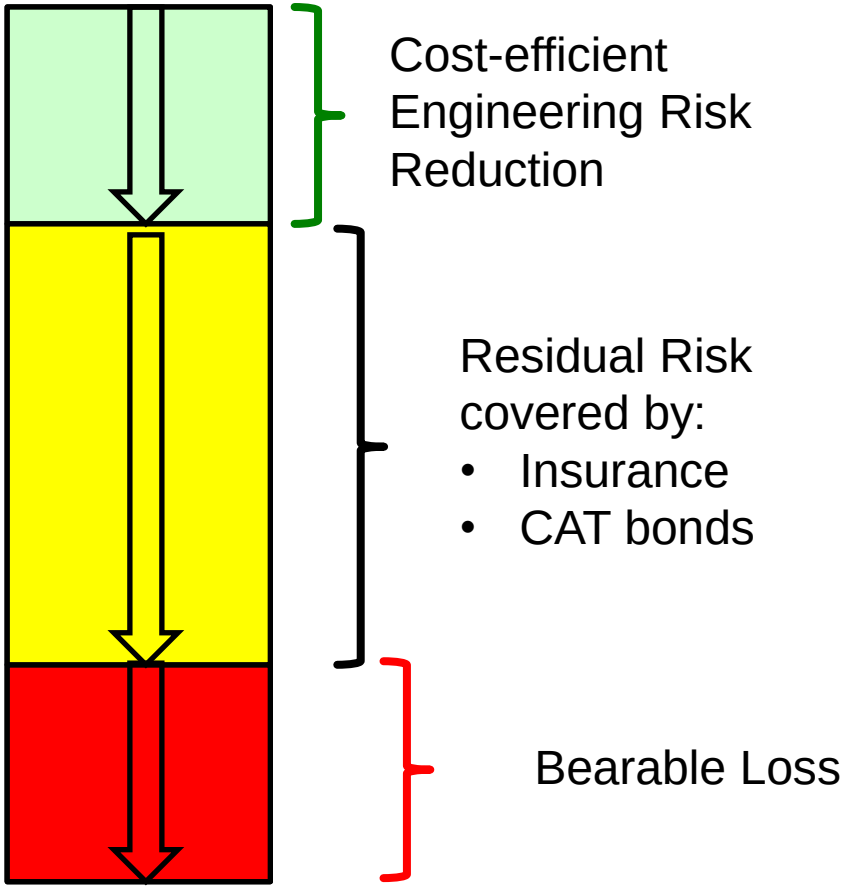
- Structural engineering measures:
  - Actuarial price or new construction or retrofit
- Financial engineering measures:
  - Viable risk transfer models
- Public policy measures:
  - Minimize the remaining losses



After SwissRe Sigma 1/2014

Financing Engineering Community Resilience

- Provide for investments to reduce vulnerability before the event:
  - Community taxes
  - Municipal bonds
- Provide the means for rapid recovery:
  - Catastrophe bonds
  - Earthquake Insurance
- Promote risk reduction through public policies



After SwissRe Sigma 1/2014

Challenge:
Engineering Resilient Communities

- Preparedness
- Component and System Engineering
- Urban planning
- Financial and Public policy

- Community risk is increasing:
  - Investment in community resilience is as important as investment in innovation and new technologies
- Engineering resilient communities is a key element of societal risk governance

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  - Dr. John-Michael Wong
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hvala
sagolun
takk
taiku
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