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Modeling Interdependent CI Systems for Seismic Resilience Evaluation and Design

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1

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Community:

Geographically bounded entity with shared history and future




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Community Resilience

- Not giving up
 - Continuity of community existence through the survival of its inhabitants and the continuity of its social and economic functions
- Hypothesis:** community resilience depends on the resilience of its built infrastructure



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

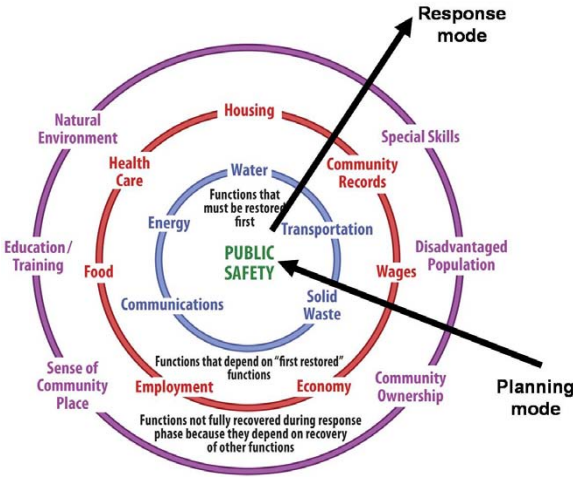
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Community Functions and Its Civil Infrastructure Systems

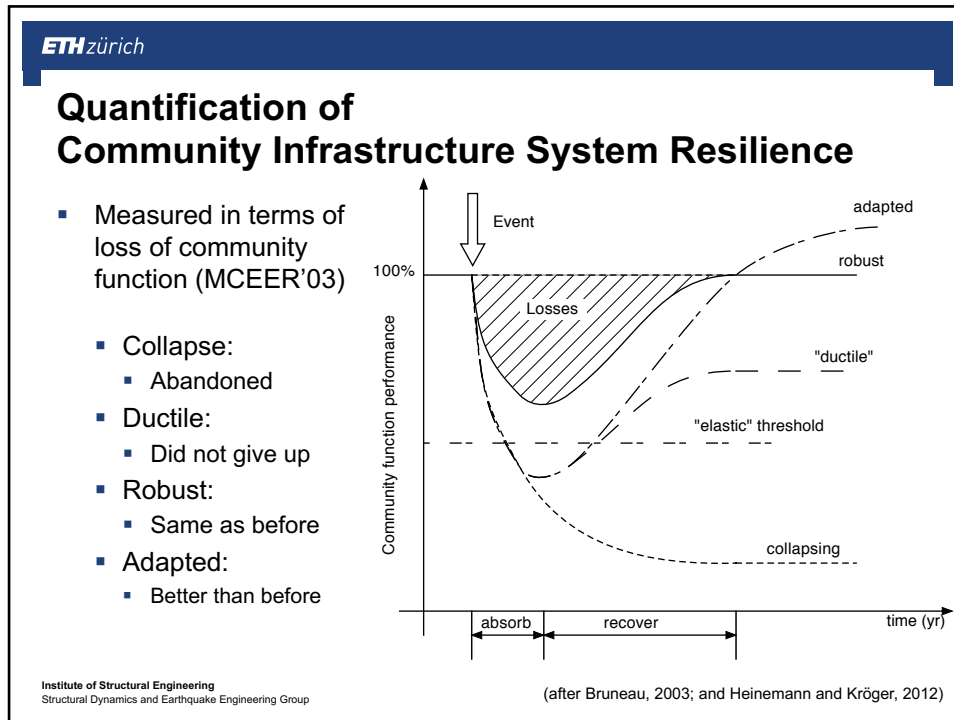
- Safety
- Physical infrastructure:**
 - Energy
 - Water
 - Communication
 - Transportation
 - Waste
- Health and Economy
- Social:
 - Culture
 - Heritage
 - Education...



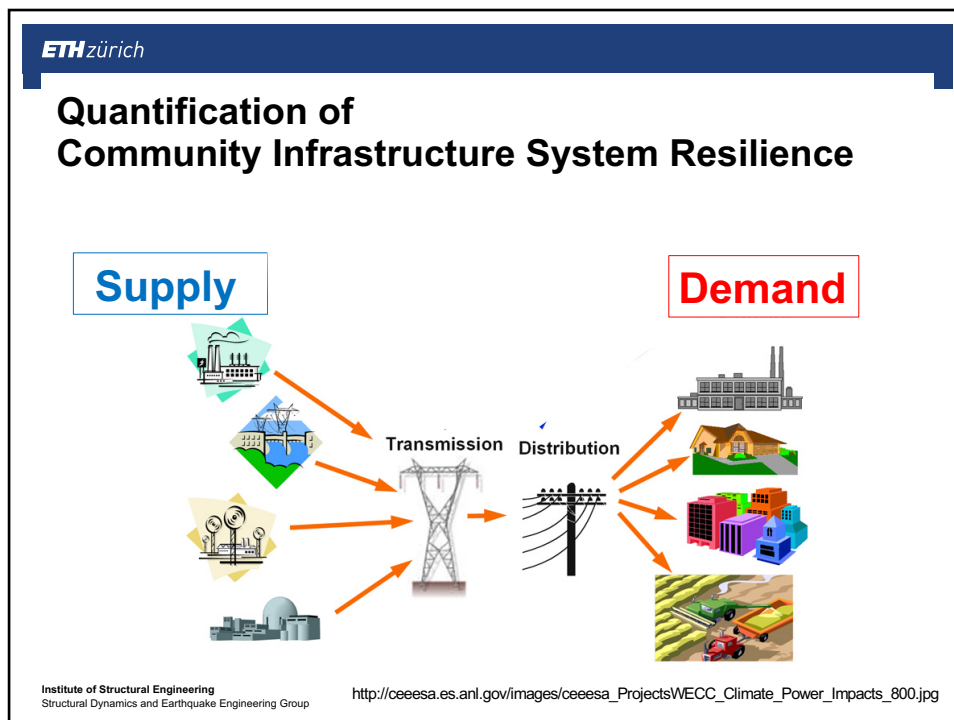
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Raking of Important community functions (SERRI and CARRI, 2009)

4



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Quantification of Community Infrastructure System Resilience

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

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Quantification of Community Infrastructure System Resilience

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

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Supply/Demand Formulation to Quantify Community Infrastructure Resilience

- Lack of Resilience** is the unmet demand of the community for the considered resource:
 - Power, water, communication...

$$LoR_{sys,r} = \int_{t_0}^{t_f} (D_{sys,r}(t) - C_{sys,r}(t)) dt$$

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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*.

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Re-CoDeS Framework

supply nodes

supply capacity
 $S_{C,i}, S_{C,sys} = \sum S_{C,i}$

system level

network functioning model

distribution nodes

demand
 $D_i, D_{sys} = \sum D_i$

available supply (to distribute)
 $S_{av,j}, S_{av,sys} = \sum S_{av,j}$

consumption
 $C_i = \min(S_{av,i}, D_i), C_{sys} = \sum C_i$

considered elements:

- efficiency losses of supply facilities (e.g. due to ageing)
- damages of supply facilities

considered elements:

- transmission losses
- network inefficiencies
- link capacity limitations
- link damages
- allocation strategy

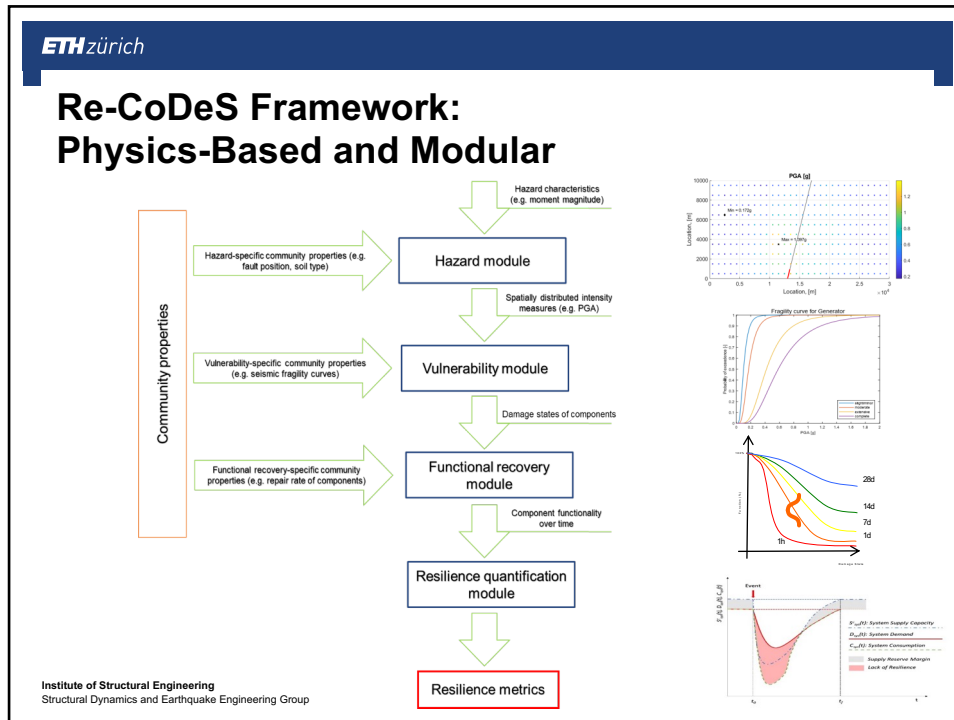
considered elements:

- efficiency losses of distribution facilities (e.g. due to ageing)
- damages of distribution facilities

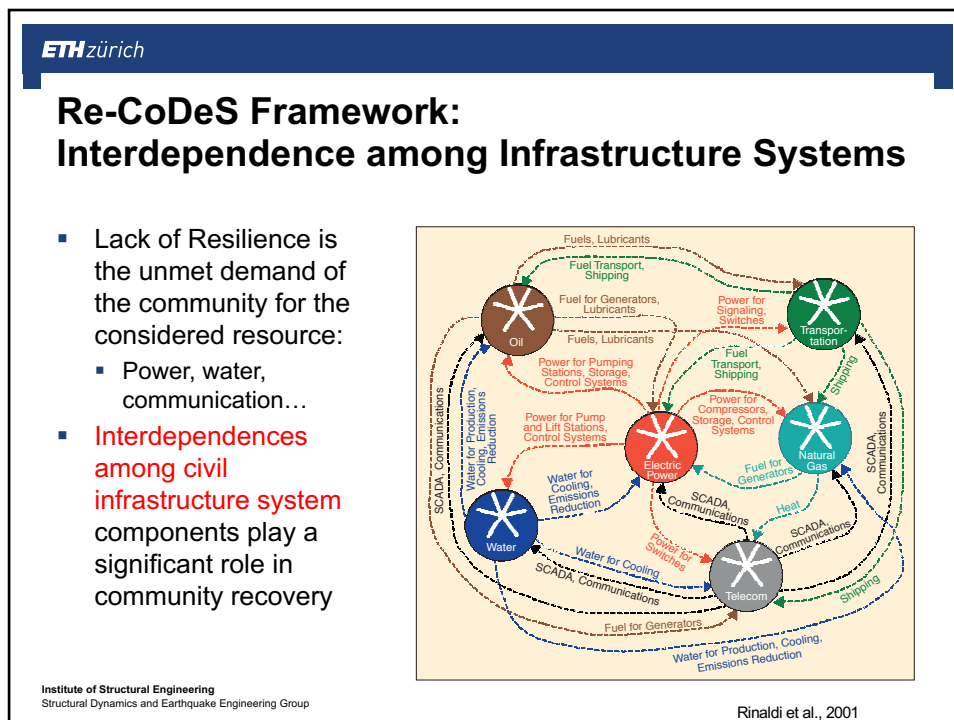
More details in:
<https://doi.org/10.1080/23789689.2017.1364560>

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10



12

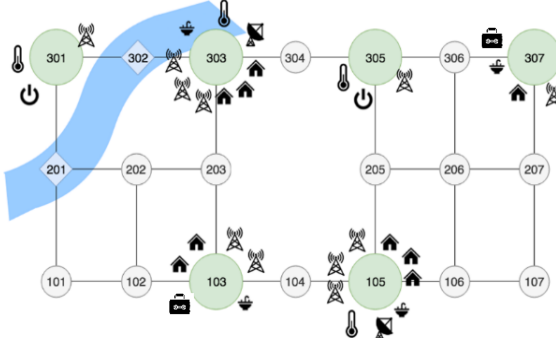


13

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A Virtual Community

- Area of 10 x 30 km
- Housing for 3600 inhabitants
- Three infrastructure systems:
 - Electric Power Supply
 - Cellular Communication
 - Water Supply
- Three types of links:
 - Power lines
 - Water pipes
 - Roads (to transport repair crews, machinery and material)



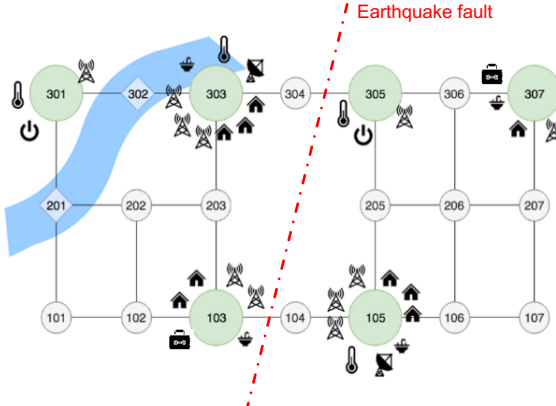
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A Virtual Community: Seismic Hazard and Risk

- Area of 10 x 30 km
- Seismic hazard:
 - Origin
 - Intensity and likelihood
 - Geographic extent
 - Predictability
- Community inventory:
 - Exposure
 - Vulnerability
 - Recovery
 - Safety
 - Function



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A Virtual Community: Interdependence among Infrastructure Systems

- Community components are dependent on each other for function
- Interdependencies among infrastructure systems are defined at the component level

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A Virtual Community: Interdependence among Infrastructure Systems

- Restoration of component function depends on:
 - Its damage
 - Resources needed for recovery
 - Start and rate of its recovery
 - Availability of resources it needs to function:
 - A generator needs cooling water and communication

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A Virtual Community: Interdependence among Infrastructure Systems

Pre-disaster state:
 Supplies: 3MWh of power
 Demands: 1MWh, 1E, 1M/day
 Supplies: 3M/day of cooling water
 Demands: 0.5MWh
 Supplies: 2E of cellular communication
 Demands: 0.5MWh, 0.5M/day

Post-disaster state (t = 0):
 Supplies: 2MWh
 Demands: 3MWh, 1E, 1M/day
 Supplies: 1.4M/day
 Demands: 0.5MWh
 Supplies: 3E
 Demands: 0.5MWh, 0.5M/day

Iteration process at time step 0

Distribute:	Power (MWh)	Cellular communication (E)	Cooling water (M/day)
Run 1	In the system: 2MWh - 1MWh = 1MWh 0.5MWh 1MWh - 0.5MWh = 0.5MWh 0.5MWh 0.5MWh - 0.5MWh = 0MWh Supply margin: 0 MWh	In the system: 3E 1E 1E - 1E = 0E 0E 0E Supply margin: 0 E	In the system: 1.4M/day 1.4M/day 1.4M/day - 1M/day = 0.4M/day 0.5M/day 0.4M/day - 0.5M/day < 0 Supply margin: 0.4 M/day
Run 2	In the system: 2MWh - 1MWh = 1MWh 0.5MWh 1MWh - 0.5MWh = 0.5MWh 0.5MWh 0.5MWh - 0.5MWh = 0MWh Supply margin: 0 MWh	In the system: 3E 1E 1E - 1E < 0E 0E 0E - 0E = 0E Supply margin: 0 E	In the system: 1.4M/day 1.4M/day 1.4M/day - 1M/day = 0.4M/day 0.5M/day 0.4M/day - 0.5M/day < 0 Supply margin: 0.4 M/day
Run 3	In the system: 0MWh - 1MWh < 0E 0.5MWh 0MWh - 0.5MWh < 0E 0.5MWh 0MWh - 0.5MWh < 0E Supply margin: 0 MWh	In the system: 3E 1E 1E - 1E < 0E 0E 0E - 0E < 0E Supply margin: 0 E	In the system: 0MWh/day 0MWh/day 0MWh/day - 1M/day < 0E 1M/day 0MWh/day - 0.5M/day < 0E 0.5M/day 0MWh/day - 0.5M/day < 0E Supply margin: 0 M/day

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A Virtual Community: Post-Earthquake Recovery Simulation

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A Virtual Community: Post-Earthquake Recovery Animation

Time Step: 1

• Power Lines Water Pipes - - - Roads

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A Virtual Community: Effect of Interdependencies

Demand, Supply Capacity, Consumption [MWh]

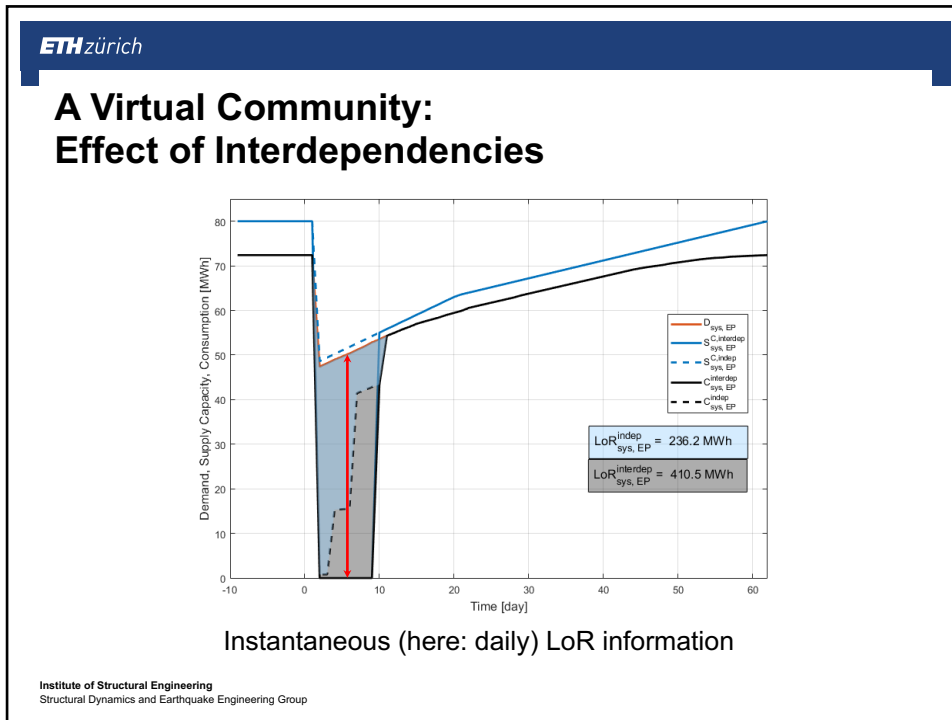
Time [day]

LoR^{indep}_{sys, EP} = 236.2 MWh
LoR^{interdep}_{sys, EP} = 410.5 MWh

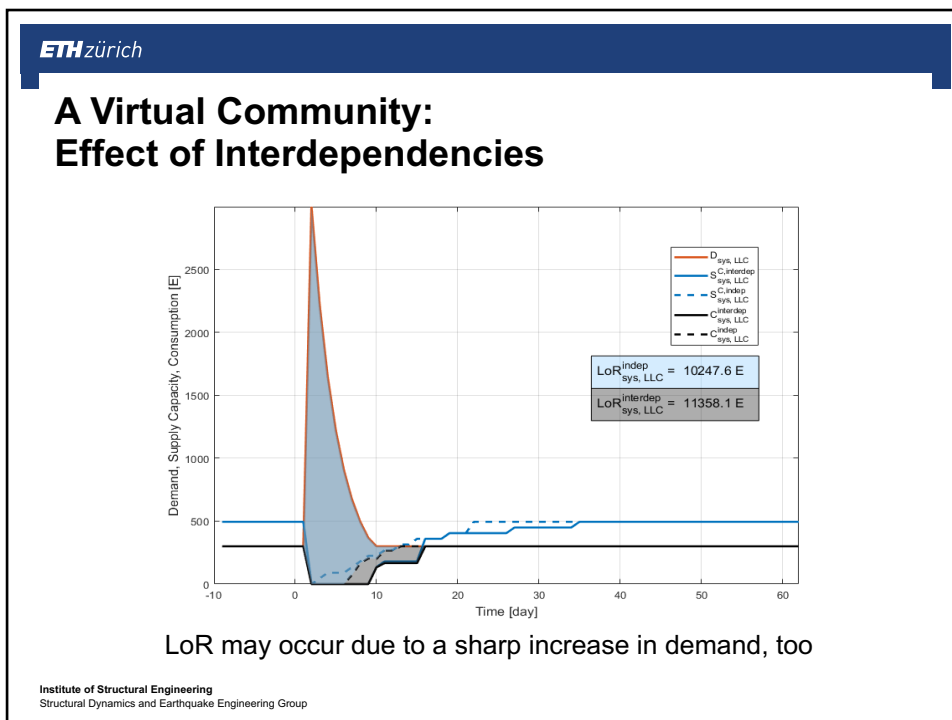
Interdependencies increase LoR of EPS by 74%

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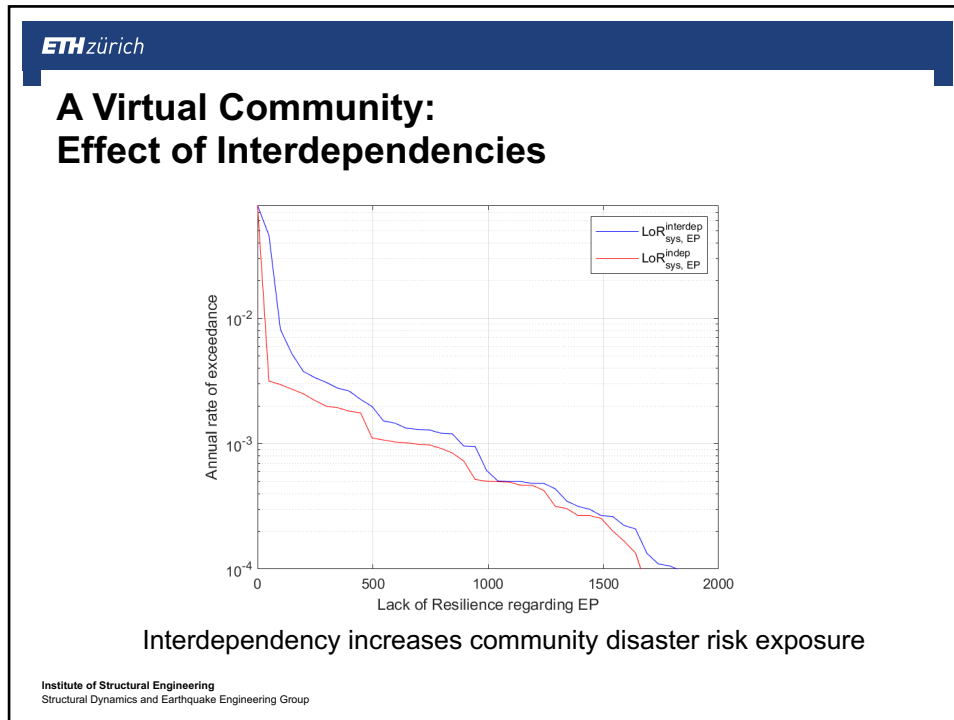
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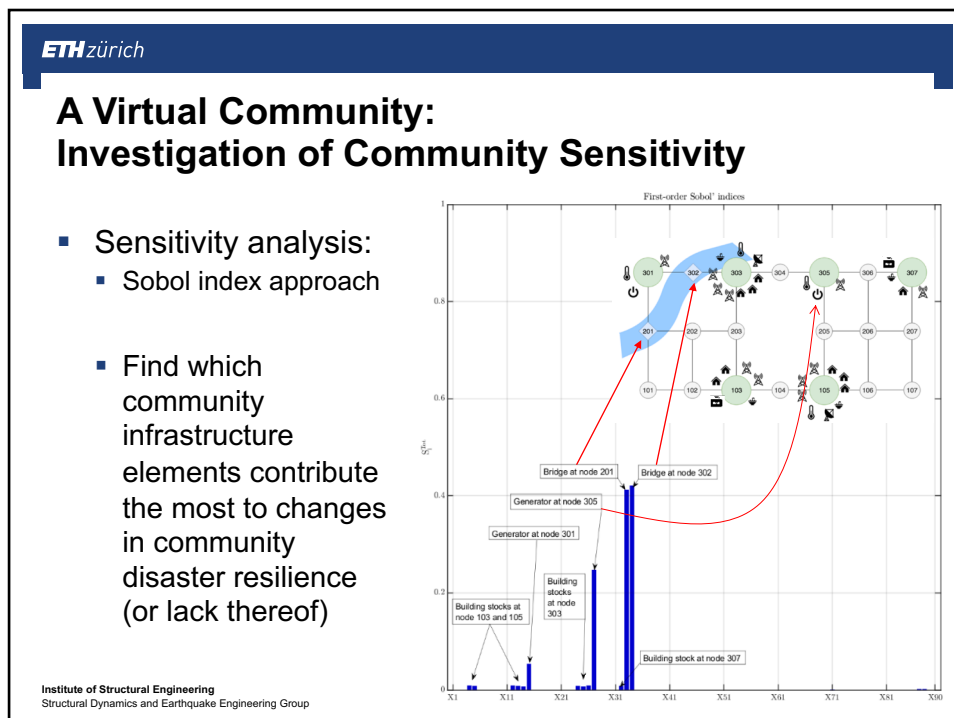
22



23



24



25

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A Virtual Community: Optimization of Disaster Preparedness Actions

- Optimize the amount of resources and services needed for recovery
- Recourses:
 - Repair crews
 - Repair materials
 - Repair machinery
 - Emergency services
 - Mobile power generators**
 - Satellite phones
 - Water supply trucks

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Challenge: Make Communities more Resilient

- Community risk is increasing:
 - Population growth
 - Productivity and innovation
- Resilience is systemic**
- Engineering resilient communities is a key element of societal risk governance
 - Re-CoDeS framework can be used for community resilience evaluation and design

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<https://www.nytimes.com/2019/07/16/opinion/smart-cities.html>

27

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30