The Interdependent Networked Community Resilience Modeling Environment (IN-CORE) of the NIST-funded Center for Risk-Based Community Resilience Planning

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Introduction: Motivation

- **Community resilience depends on the performance of the built environment and on supporting social, economic, and public institutions** that are essential for immediate response and long-term recovery of a community following a damaging event
- The performance of the built environment, which is a key factor in community resilience, is largely determined by codes and standards, which are applicable to individual facilities and have the primary objective of preserving life safety under design-level hazard events
- However,
  - current codes do not address facility performance in the period of recovery following an event, and
  - The design of interdependent infrastructure (e.g., transportation, potable water, wastewater, electric power, and communication) currently is based on criteria developed by independent professional organizations or industry sectors with different performance objectives and design hazard levels (i.e., independent designs of interdependent infrastructure)
- **There is a need for**
  - **science-based measurement tools to evaluate performance and resilience at the community scale**
  - **fully integrated supporting databases, and**
  - **a risk-informed decision framework to support optimal life-cycle technical and social policies**

Introduction: CoE

- The National Institute of Standards and Technology (NIST) funded the Center of Excellence for Risk-Based Community Resilience Planning (CoE) to develop the measurement science needed to support community resilience
- The developed measurement science is implemented in a computational environment with fully integrated supporting databases to
  - model the impact of natural hazards on communities including recovery,
  - evaluate the key attributes that make communities resilient, and
  - optimize resilience enhancement and planning strategies
- Such Interdependent Networked Community Resilience Modeling Environment (abbreviated as IN-CORE) is built upon the MAEViz software to leverage existing work in the modeling of physical, social, and economic systems

Outline

- Background: MAEViz
- IN-CORE features
  - Hazards
  - Interdependencies among physical, economic, and social systems
  - Aging and deterioration
  - Recovery and components and systems
  - Economic systems
  - Social systems
  - Model and parameter updating
  - Optimization
- A few concluding remarks
- Additional resources

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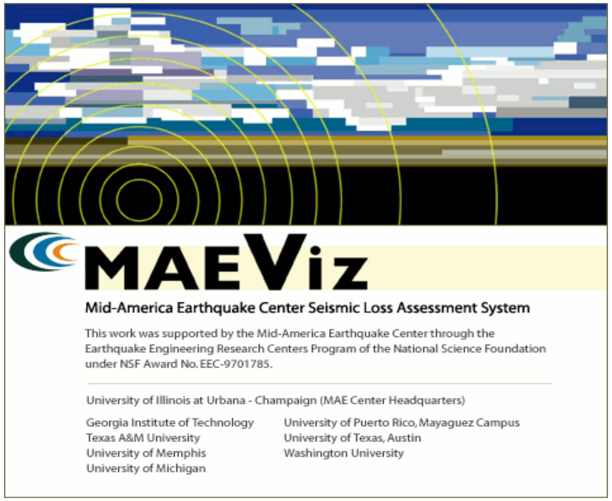
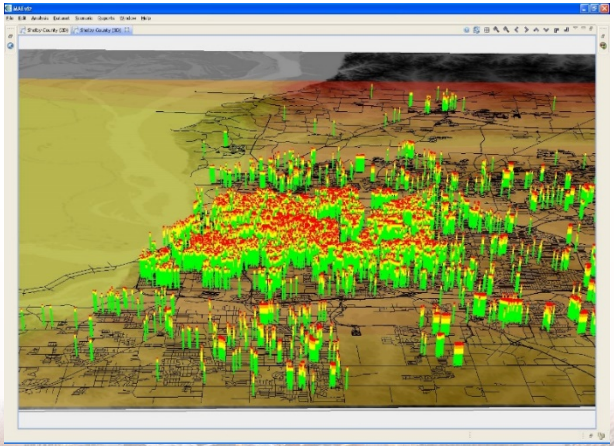
Background: MAEViz

- MAEviz was developed by Mid-America Earthquake (MAE) Center with initial funding from the National Science Foundation
- It is an advanced tool for loss assessment and risk management for buildings, bridges and other infrastructure, and for network level analysis
- It was designed to enable policy-makers and decision-makers to develop risk reduction strategies and implement mitigation actions to minimize the impact of natural hazards
- MAEViz offers several of analyses, ranging from direct seismic impact assessment; to socio-economic implications including 2D and 3D mapped visualizations of the inputs and outputs of analyses; and table, chart, graphs, and reports of the results

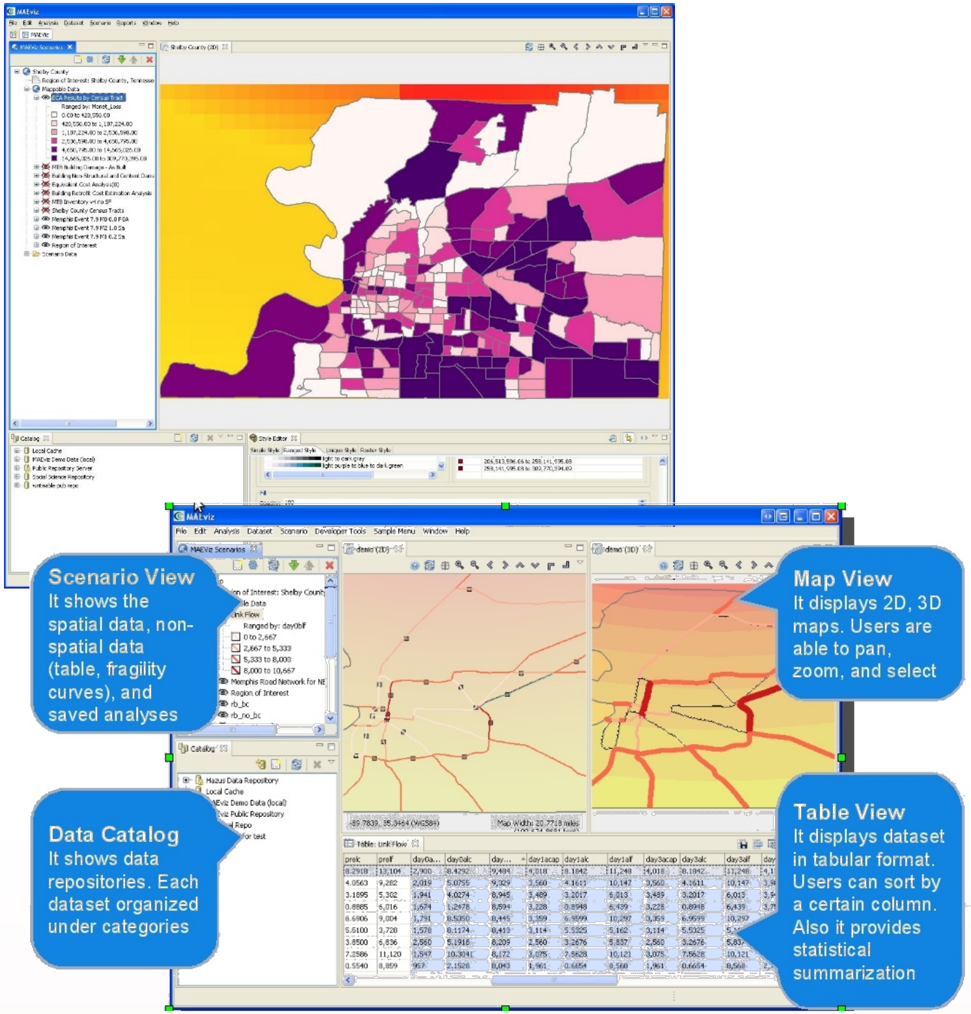


http://mae.cee.illinois.edu/



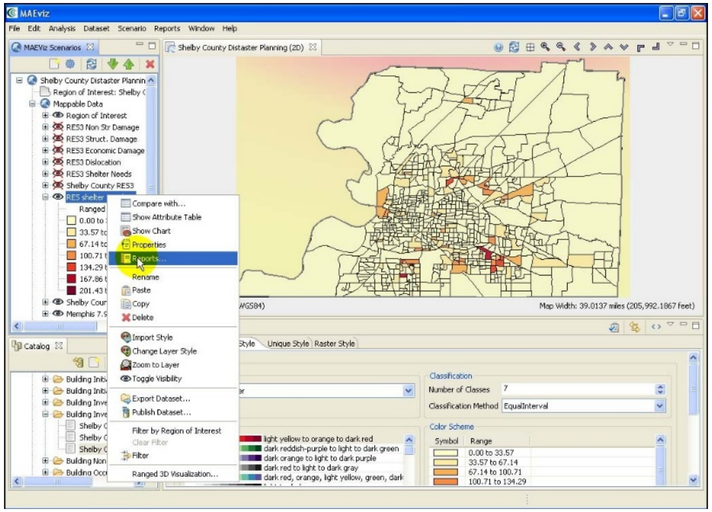
Background: MAEViz

- MAEViz provides an extensible spatial analysis environment with a visually-based, menu-driven system
  - It generates damage estimates from scientific and engineering principles and data; tests multiple mitigation strategies; and estimates impacts of hazards on structures, infrastructure and social and economic systems
  - Fragility and repair rate functions are incorporated for infrastructure systems, such as transportation, power facilities, buried pipelines for water and gas, buildings, and bridges
  - There are capabilities for modeling interdependencies, such as the interdependency between the power network and water network



Background: MAEViz

- The socio-economic analyses include
  - estimating expected indoor deaths and injuries, business interruption loss, fiscal impact due to building damage, household/population dislocation, business content and inventory loss, short term shelter needs, shelter supply needs, and
  - optimizing the temporary housing allocation



- MAEviz was originally developed for seismic hazards and later extended to include inundation due to tsunami

- The World Bank (2014) conducted a comprehensive review of open access software packages for regional risk analysis and identified MAEViz as “the best software for scenario risk assessment and decision support”

- As a result, to leverage the existing work, IN-CORE’s development started from the MAEViz software package

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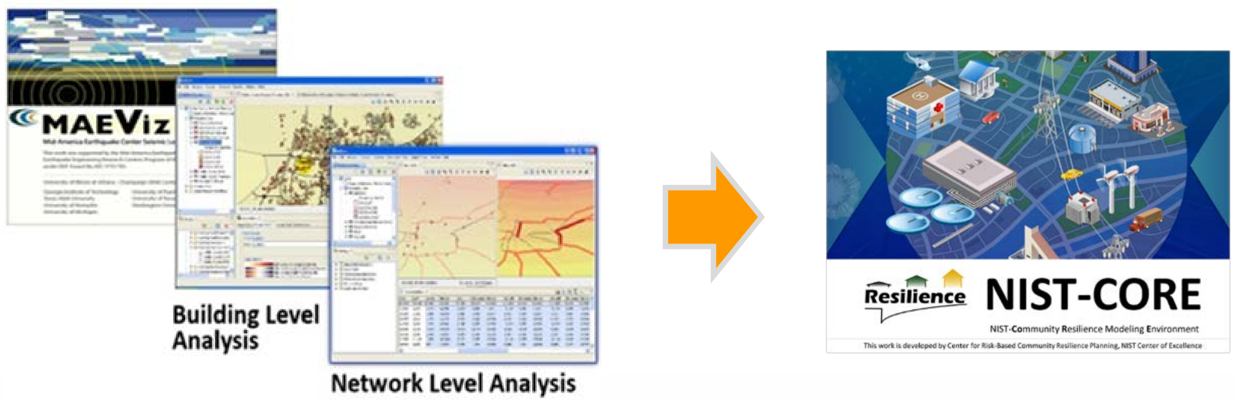
IN-CORE general features

- To better quantify community impacts and model recovery over time, IN-CORE is adding new capabilities to consider
  - multiple hazards and coupled threats
  - additional system interdependencies and cascading effects
  - the effects of aging and deterioration of structures and infrastructure and
  - new models of social and economic systems
- To enhance community resilience, optimization strategies will also be included



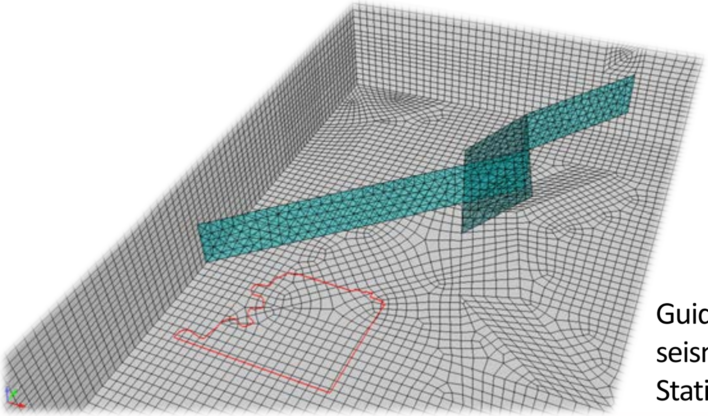
- IN-CORE v1 was released at the end of 2019 as an open-source environment with currently available features, future releases will include ongoing work

Hazard modeling

- IN-CORE considers both individual hazards and multiple hazards modeled as scenarios at the community scale to capture the spatial distribution of the demands
- Two levels of models are available in IN-CORE, namely Tiers 1 and 2
  - Tier 1 hazard models will be executed completely within IN-CORE using libraries and plug-ins developed as part of the Center of Excellence research program, and will use standard natural hazard analysis formulations
  - Tier 2 hazard models will provide an option to import hazard data from analyses conducted outside of IN-CORE

Hazard modeling

- For example, for earthquakes
  - The Tier 1 earthquake scenario will require the analyst to select an attenuation equation from the library available in IN-CORE and specify the relevant parameters (the option of weighting multiple GMP equations is also available)
  - The Tier 2 earthquake scenario will involve running an analysis externally, for example, running a high-resolution, 3-dimensional (3D), physics-based model for seismic wave propagation and importing the ground kinematics into IN-CORE

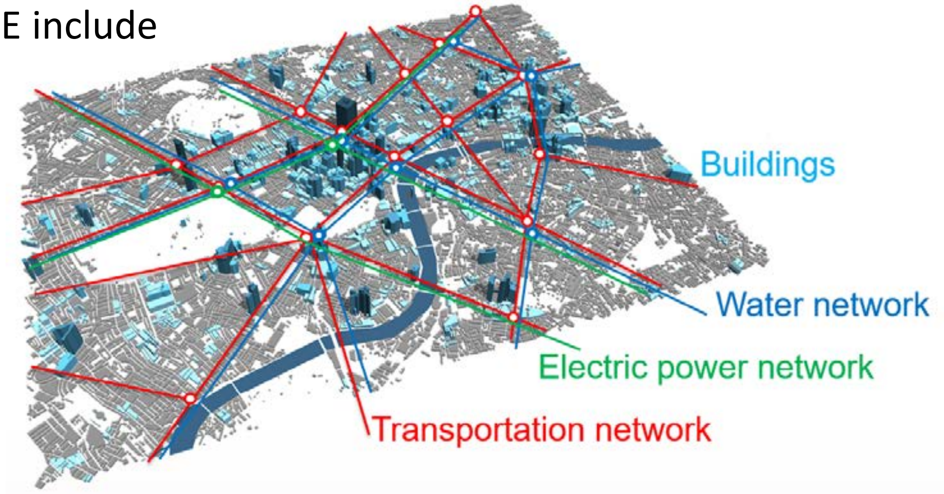


Guidotti, R., Tian, S., and Gardoni, P. "Simulation of seismic wave propagation in the Metro Memphis Statistical Area (MMSA)" (in preparation).

- Other hazards modeled with 1 or 2 tiers include windstorms, tornados, hurricanes, wildland-urban interface fires, tsunamis, and floods

Physical infrastructure and social and economic systems

- **Physical infrastructure** modelled in IN-CORE include
  - Buildings
  - Transportation
  - Water and Wastewater
  - Energy
  - Telecommunications

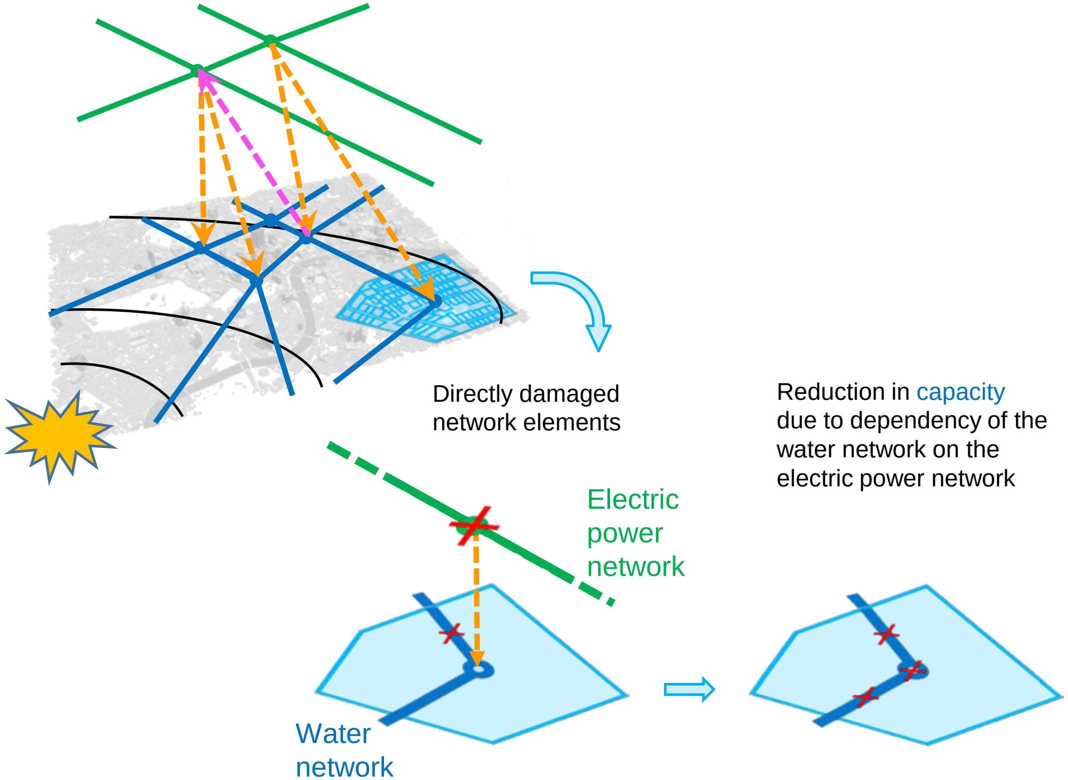


- Models of the **social systems** focus on population and employee dislocation, housing restoration and recovery, and business interruption and restoration
- Models of the **economic systems** focus on the prediction of economic damages, such as production, job, and wage losses in various local economic sectors and their subsequent impacts on residents, including health, income and migration

Physical infrastructure often depend on each other and such dependencies might indirectly affect a network capacity

Some examples

- Buildings need the service provided by the water and power networks
- The water network depends on the power network because it needs power at the pumping stations and control systems
- The electric power network needs fuel for generators and water for cooling
- The transportation network needs power for signaling
- The water network needs the transportation network to access the locations of critical elements



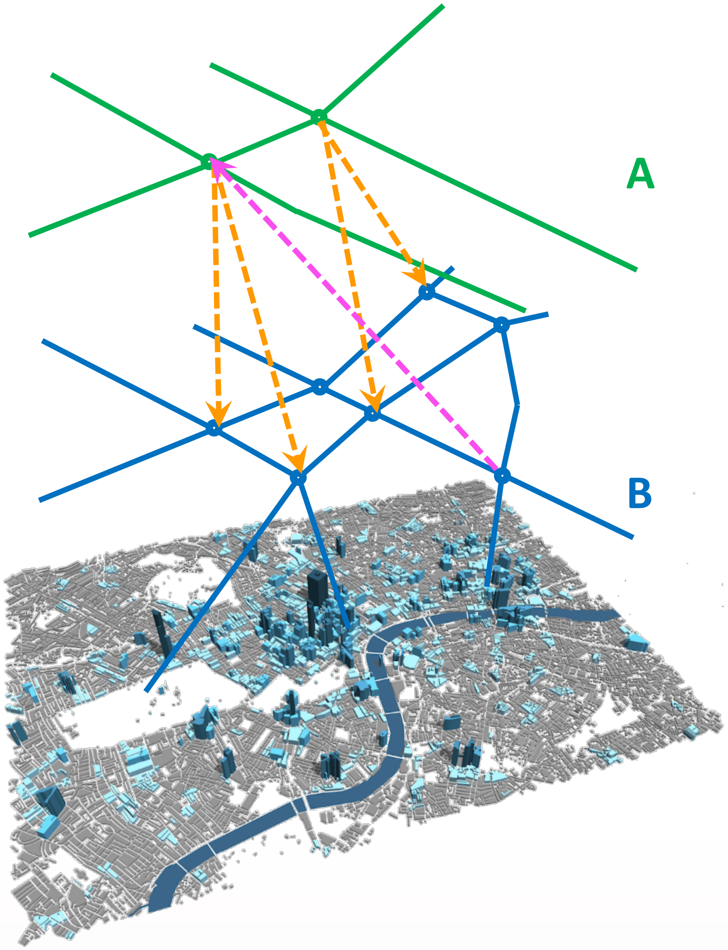
Guidotti, R., Gardoni, P., and Rosenheim, N., (2019) "Integration of physical infrastructure and social systems in communities' reliability and resilience analysis," *Reliability Engineering & System Safety*, 185, 476-492.

Sharma, N., Nocera, F., and Gardoni, P. (2019). "Classification and mathematical modeling of infrastructure interdependencies," *Sustainable and Resilience Infrastructure* (under review).

As a result, even if a network has no physical damage, there could be a loss or reduction of functionality of such network…

… because of the physical damage (and corresponding loss of functionality) of a supporting network

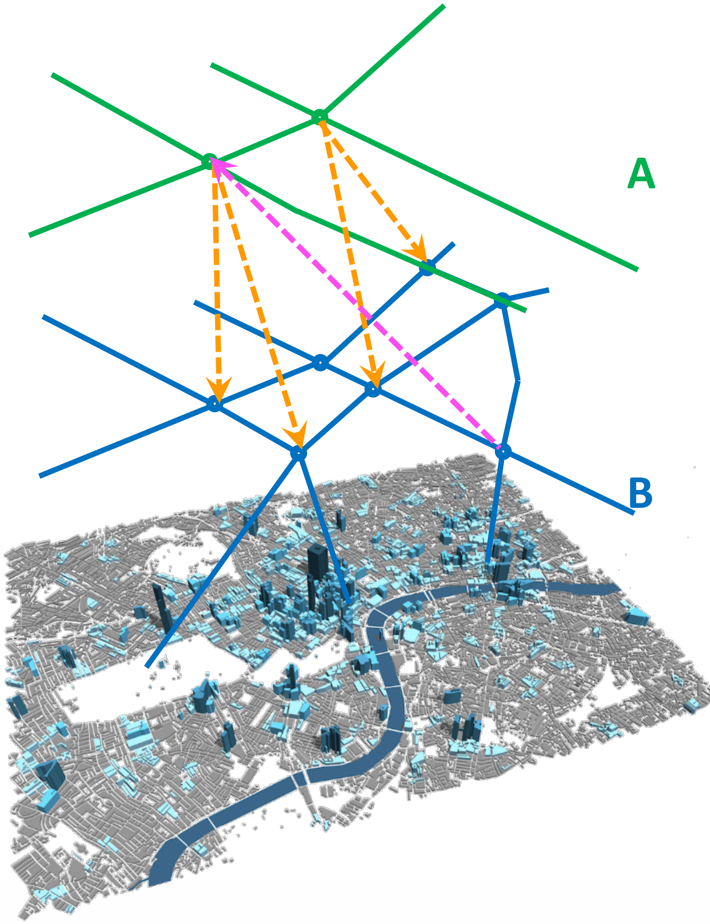
- We need to translate the physical damage into loss or reduction in functionality and then propagate such loss or reduction across all dependent networks (Guidotti et al. 2016)



Guidotti, R., Chmielewski, H., Unnikrishnan, V., Gardoni, P., McAllister, T., and van de Lindt, J. (2016). "Modeling the resilience of critical infrastructure: the role of network dependencies," *Sustainable and Resilient Infrastructure*, 1(3-4), 153-168.

Interdependency and damage modeling

- IN-CORE models **interdependencies** among physical infrastructure systems (Guidotti et al. 2016)
  - Interdependencies can change over time depending on the level of initial damage and the recovery process
- This modeling capability is being extended to the interdependencies between social and economic systems and physical infrastructure (Guidotti et al. 2019)



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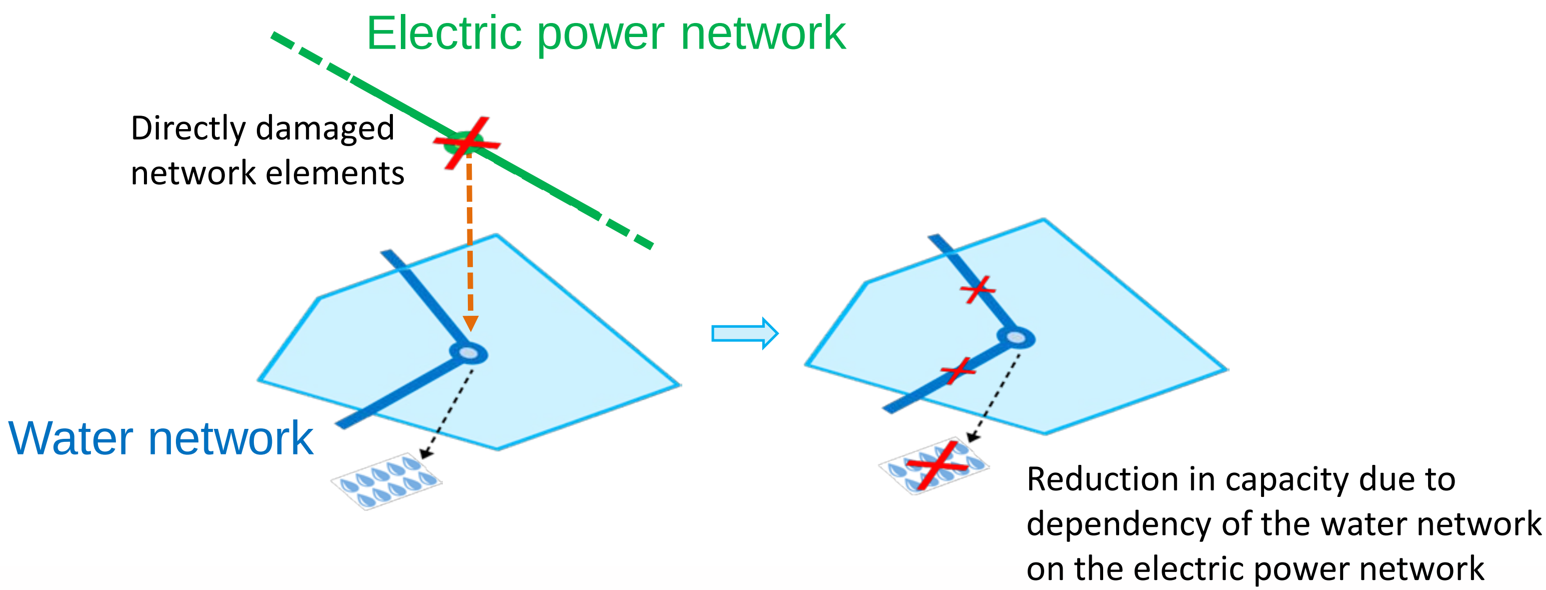
For example, considering the water network

- IN-CORE can model the change in the **capacity** of the water network due to both the direct damage to the water network and the damage to the supporting electric power network (Guidotti et al. 2016)
  - Capacity of the water network refers to its ability to deliver a certain amount of water of minimum quality and at a minimum pressure



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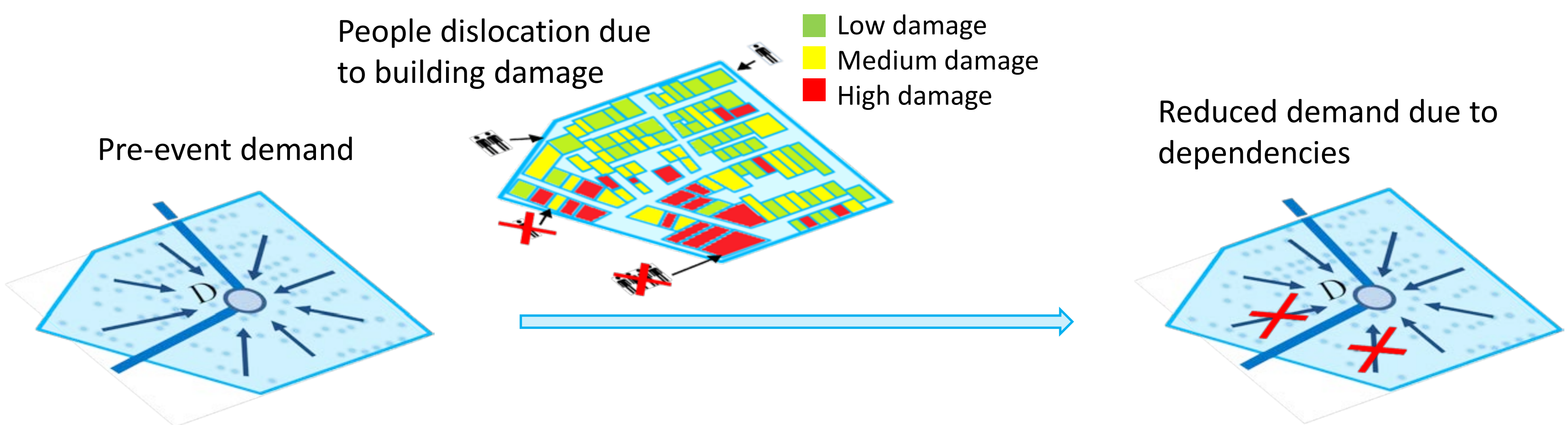
Not only the capacity, also the demand can be affected by dependencies

- For example, building damage can lead to people dislocation or business interruption that affect the post-event water network **demand** (Guidotti et al. 2019, Rosenheim et al. 2019)



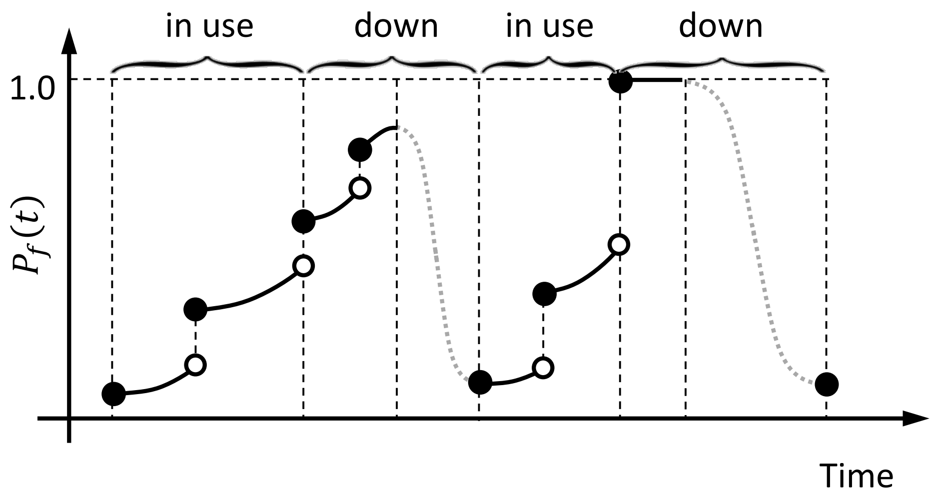
- The updated network **capacity** and **demand** can then be used in a flow-based network analysis to assess the functionality and reliability of the network

Guidotti, R., Gardoni, P., and Rosenheim, N. (2019) “Integration of physical infrastructure and social systems in communities’ reliability and resilience analysis,” *Reliability Engineering & System* Safety, 185, 476-492.

Rosenheim, N., Guidotti, R., Gardoni, P., and Peacock, W. (2019). "Integration of detailed household and household unit characteristic data with critical infrastructure for post-hazard resilience modeling," *Sustainable and Resilient Infrastructure,* DOI: 10.1080/23789689.2019.1681821.

Infrastructure suffer from aging and deterioration over time

- Infrastructure may be subject to multiple deterioration mechanisms (gradual and shock)
  - e.g., an RC bridge may be subject to steel corrosion, ASR, and seismic damage
- Changes in the material and geometry can lead to higher vulnerability to hazards (higher fragility curves, repair rates and probabilities of failure or reduction in functionality)



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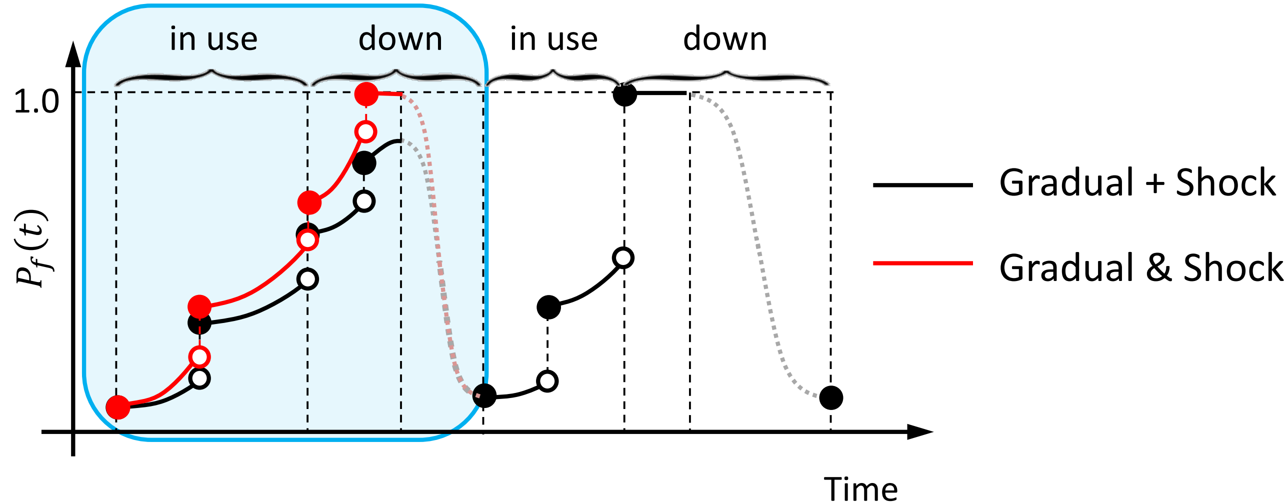
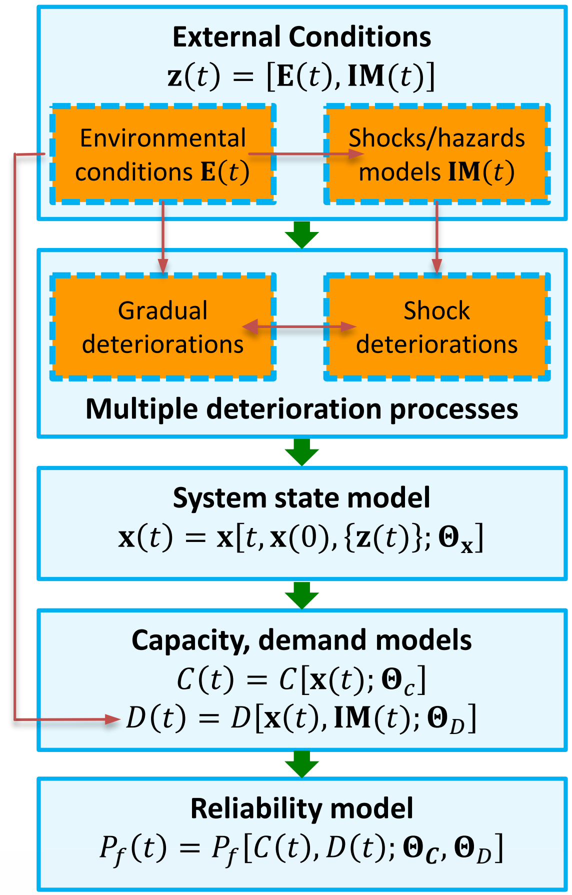


- There may be interactions between different deteriorations that accelerate the deterioration
  - e.g., the cracks in RC caused by seismic damage could accelerate the corrosion rate of steel
- Formulations available in literature do not take into account the possible interactions between the different processes

Aging and deterioration modeling

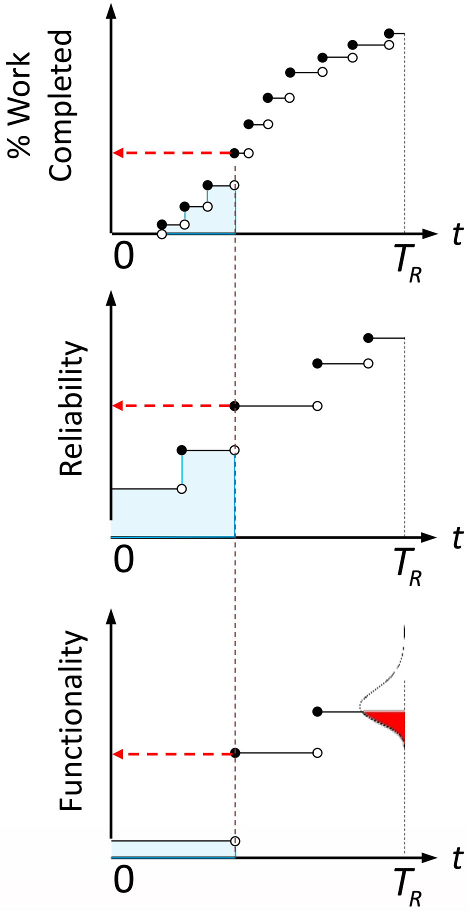
- IN-CORE will incorporate the effects of **aging and deterioration** on infrastructure components and the corresponding time-variant fragilities and repair rates
- A state-dependent formulation will allow us to model the deterioration **accounting for the possible interactions** among different deterioration processes (Jia and Gardoni 2018)
- The users will have the option to specify the input parameters that are needed in the relevant aging and deterioration models (e.g., age, environmental conditions, loading/hazard conditions, spatial variability for large infrastructure network)



Jia G. and Gardoni P. (2018). "State-dependent stochastic models: A general stochastic framework for modeling deteriorating engineering systems considering multiple deterioration processes and their interaction," *Structural Safety*, 72, 99-110.

Recovery modeling

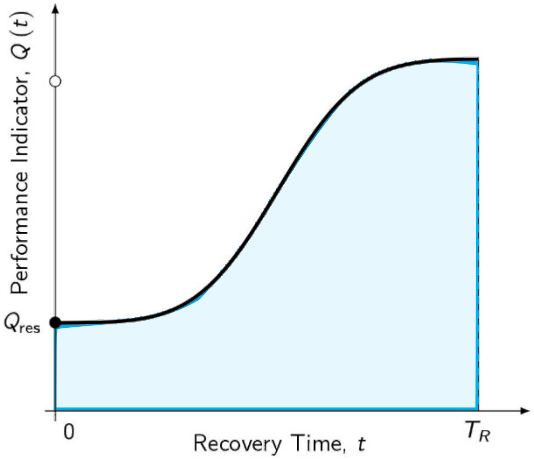
- IN-CORE will include the modeling of the recovery of the functionalities of (Sharma et al. 2018)
  - **Buildings**: Recovery of functionality for intended use
  - **Transportation**: Recovery of routes to critical facilities and critical infrastructure components
  - **Water/wastewater**: Recovery of services to buildings and infrastructure systems
  - **Energy**: Recovery of services to buildings and infrastructure systems
  - **Telecommunications**: Recovery of services to buildings and infrastructure systems
  - **Social Systems**: Recovery of services
  - **Economic Systems**: Recovery of services



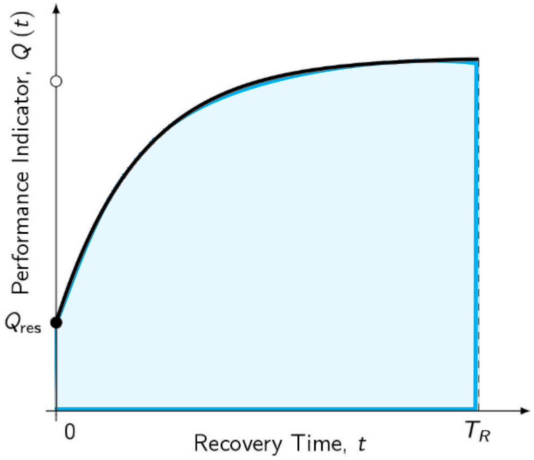
Sharma, N., Tabandeh, A. and Gardoni, P. (2018) "Resilience analysis: a mathematical formulation to model resilience of engineering systems," *Sustainable and Resilient Infrastructure*, 3(2), 49-67.

The actual shape of the recovery curve of physical components is influenced by different factors

- Including the type and level of damage, availability of resources required for the repairs, the environmental conditions, and preparedness
- Functions with different shapes have been used to model the recovery curves, where the choice of the function is based on a *qualitative* description of the situation



Lack of preparedness in the immediate aftermath but becomes more organized as time goes on



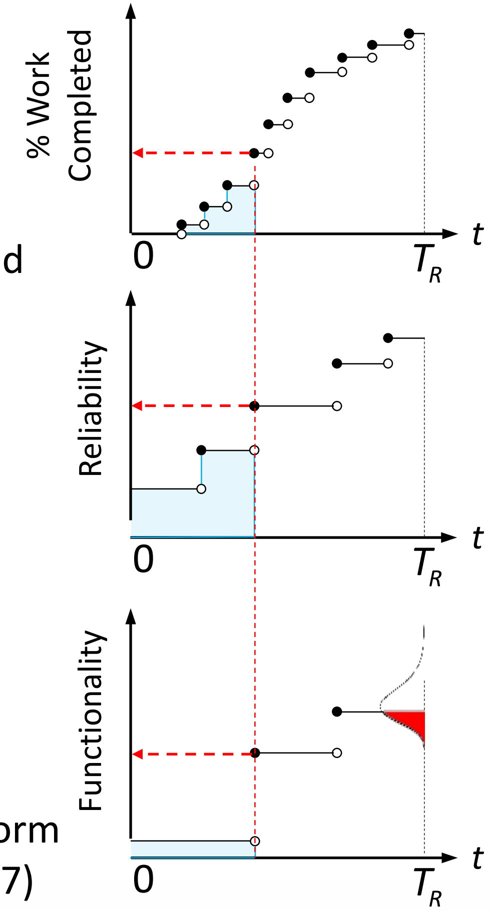
Good preparation represented by a significant progress in the immediate aftermath

To model the recovery process, we developed a stochastic formulation that accounts for the actual work progress

- This is in contrast to assuming a recovery curve
- By modeling the state variables $\mathbf{x}(t)$ during the recovery, we can estimate the capacity and demand, and then the reliability and functionality over time accounting for the relevant uncertainties (Sharma et al. 2017)
  – The work in the recovery may progress over time but the reliability and functionality of the system changes only when a group of activities is completed

$$\mathbf{x}(t) = \sum_{i=1}^{\infty} \underbrace{\mathbf{x}(t_{r,i-1})}_{\text{State variables after the completion of the recovery step at } t_{r,i-1}} \mathbf{1}_{\{t_{r,i-1} \le t < t_{r,i}\}} + \sum_{i,j=1}^{\infty} \underbrace{\Delta\mathbf{x}(t_{s,j})}_{\text{Impact of a disrupting shock on state variables at } t_{s,j}} \mathbf{1}_{\{t_{r,i-1} < t < t_{r,i},\, t_{r,i-1} < t_{s,j} \le t\}}$$

- We combined this stochastic formulation for recovery with the state-dependent formulation for deterioration (which also models $\mathbf{x}(t)$), to perform a complete life-cycle analysis using stochastic renewal theory (Jia et al. 2017)



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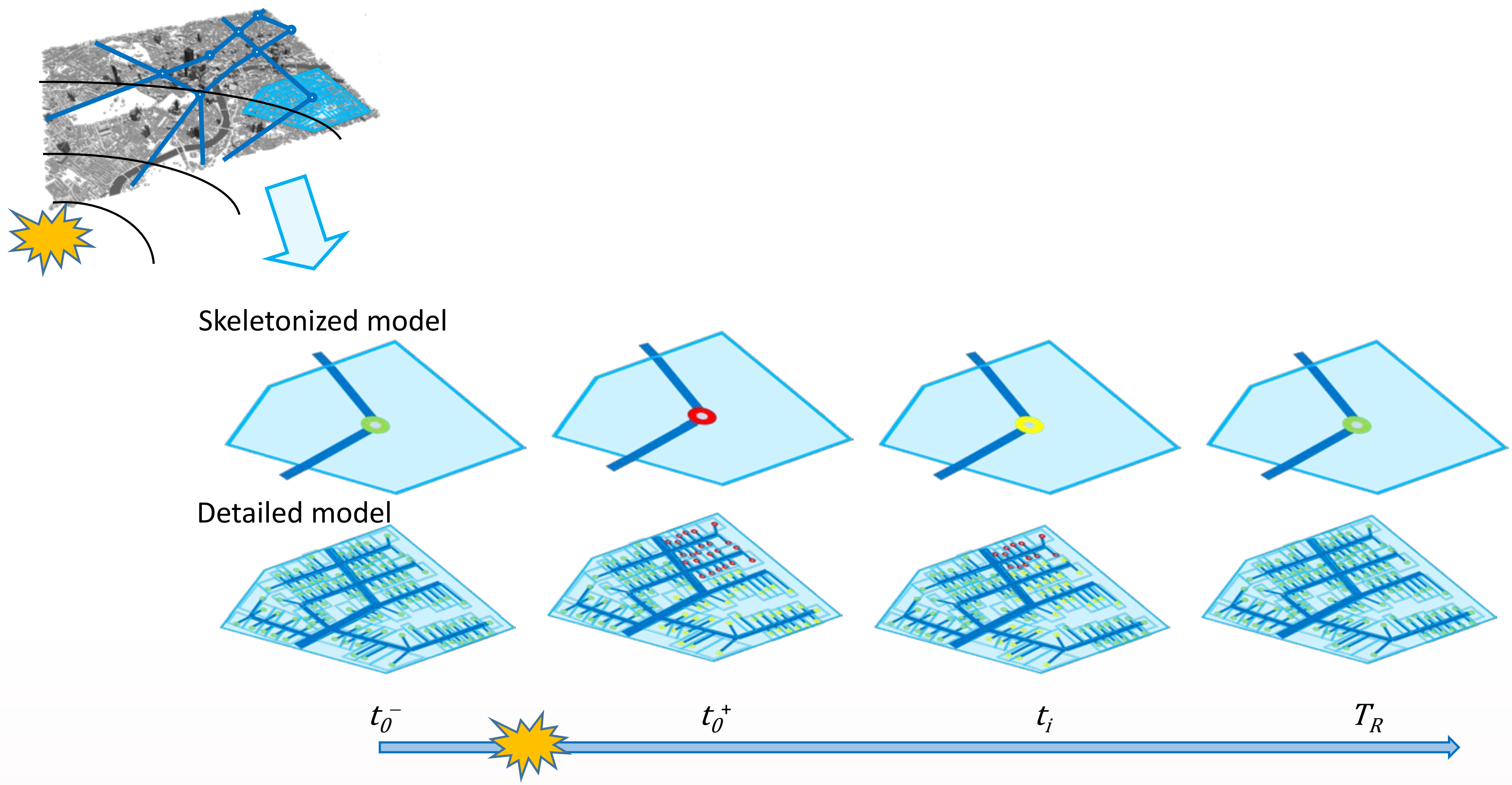
Jia, G., Tabandeh, A. and Gardoni, P. (2017) "Life-cycle analysis of engineering systems: Modeling deterioration, instantaneous reliability, and resilience." in Paolo Gardoni (Ed.), *Risk and Reliability Analysis: Theory and Applications*, Springer.

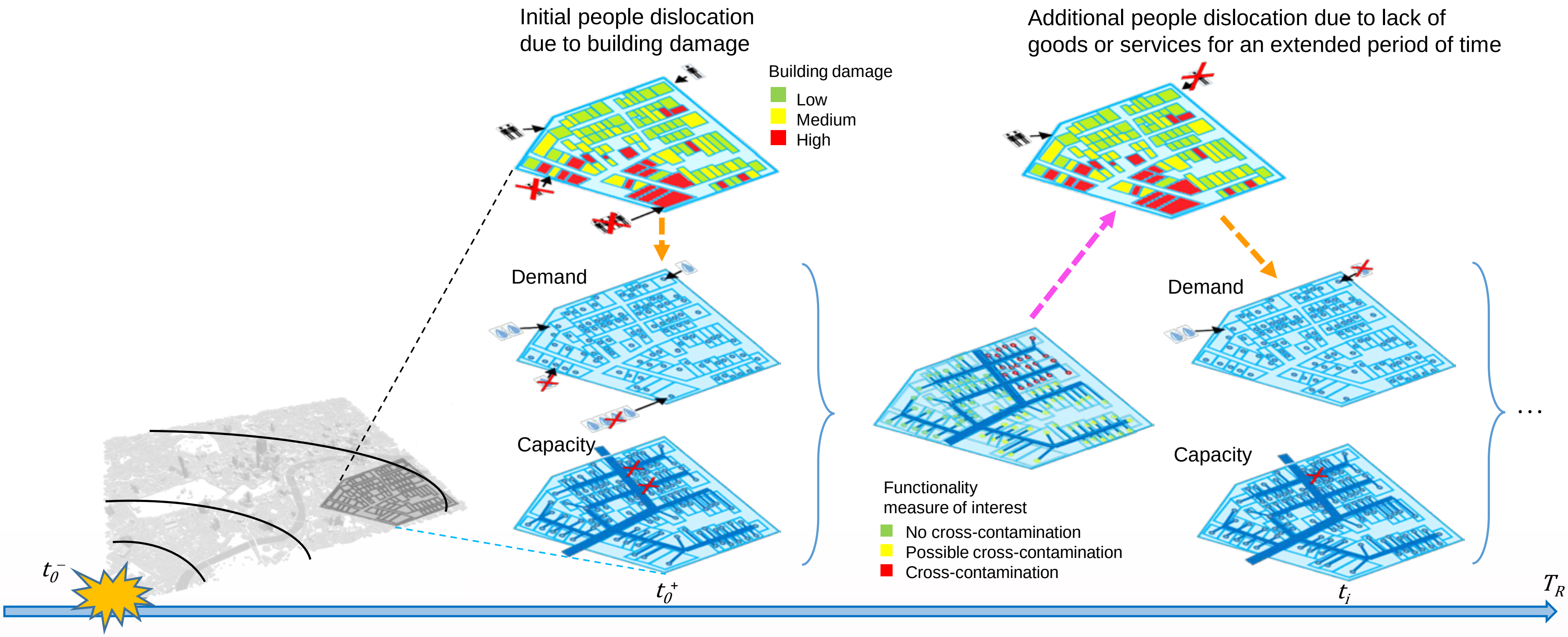
As the individual components recover, the network functionality also recovers

- The network reliability and functionality can be evaluated at different time steps, as the network components are repaired



The dependencies/interdependencies among physical infrastructure and social systems also shape the recovery process

- Lack of potable water for an extended period of time could induce further people dislocation
- The additional people dislocation could affect the water network **demand** over time in an iterative process included in IN-CORE that captures the interdependency between physical infrastructure and social systems (Guidotti et at. 2019)



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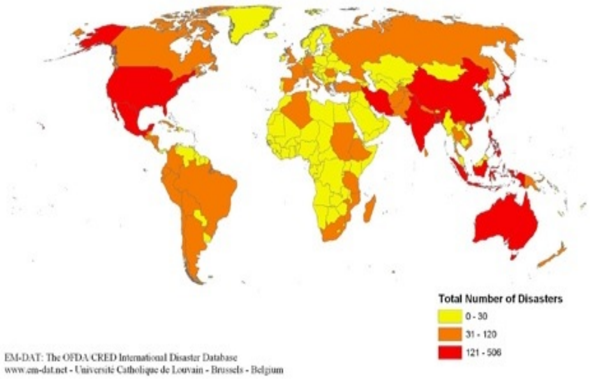
Economic systems and cascading effects

- Economic models can inform a policy portfolio of risk management investment decisions, including mitigation, warning and evacuation systems, as well as recovery and reconstruction efforts
- IN-CORE is using *applied econometric models* and *computable general equilibrium (CGE) models* to estimate the direct and cascading effects of disasters
  - Applied econometric and CGE modeling approaches are complementary because empirically estimated migration or firm formation models under critical infrastructure failure scenarios can be integrated in regional or archetypal CGE models to understand how disaster losses reverberate through labor markets, the housing stock, and various sectors of the economy
- IN-CORE will integrate *applied econometric models* and *computable general equilibrium (CGE) models* with engineering-based damage predictions to the built infrastructure to predict the direct and cascading economic impacts of natural hazards

Social systems and cascading effects

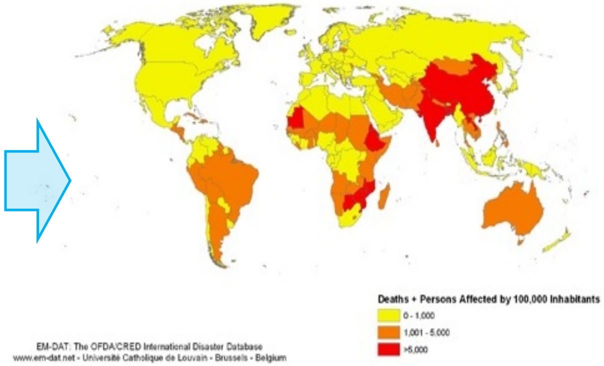
- The impacts of disasters on human populations (mortality, morbidity, and psychological) and social systems (disruption, displacement, failure, change) are heavily influenced by pre-existing inequalities related to vulnerability levels in the built, natural, economic, and social environments

Total Number of Disasters



Societal Characteristics

Number of Deaths due to Disasters



- Often vulnerable populations within communities are more likely to experience disproportionate losses, higher damage rates, and housing losses
- IN-CORE will model the cascading effects of natural hazards on social systems capturing preexisting social vulnerabilities of populations and social systems

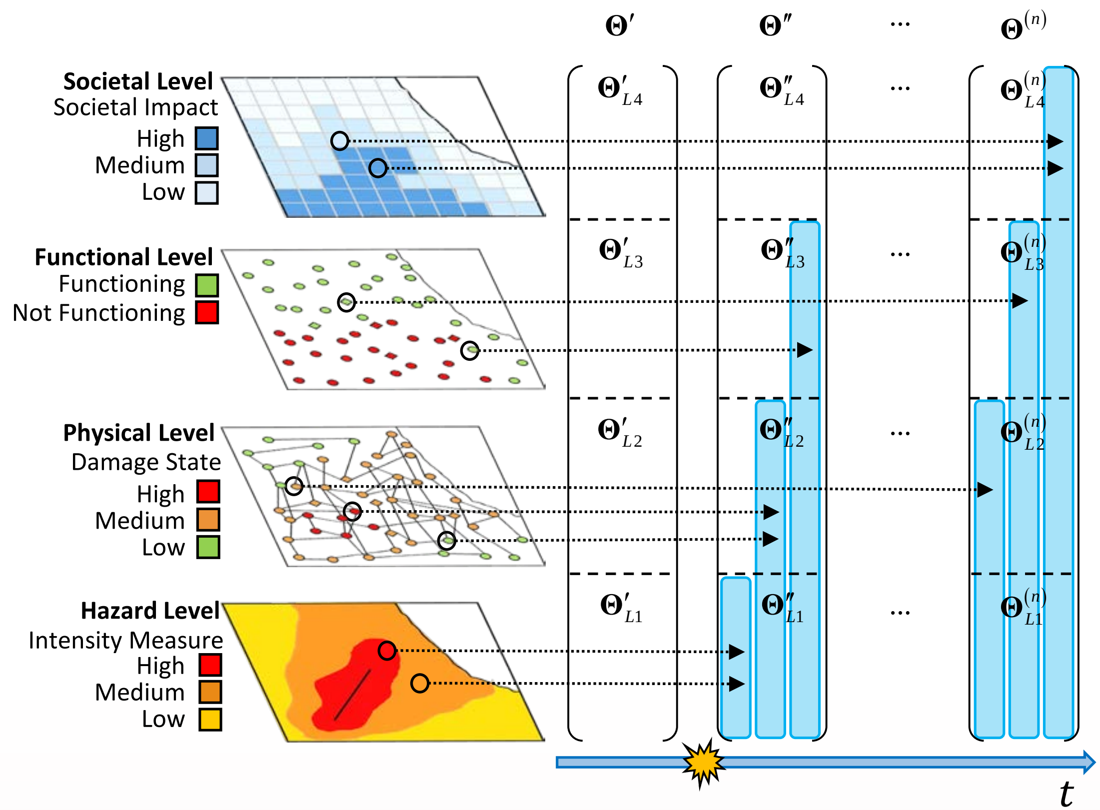
Gardoni, P., Murphy, C., and Rowell, A., (Eds.) (2016). *Societal Risk Management of Natural Hazards*, Springer.
Doorn, N., Gardoni, P., and Murphy, C., (2019). "A multidisciplinary definition and evaluation of resilience: the role of social justice in defining resilience," *Sustainable and Resilient Infrastructure*, 4(3), 112-123.
Gardoni, P., and Murphy, C., (2020). ”Society-based design: promoting societal well-being by designing sustainable and resilient infrastructure, *Sustainable and Resilient Infrastructure*, 5(1), 4-19.

Model updating

- IN-CORE will include recovery models with the ability to conduct spatial and temporal updates as field data become available

- We developed a Bayesian Updating for Probabilistic Multi-level Models of Interdependent Infrastructural Systems using Heterogeneous Field Data (Guidotti et al. 2019)

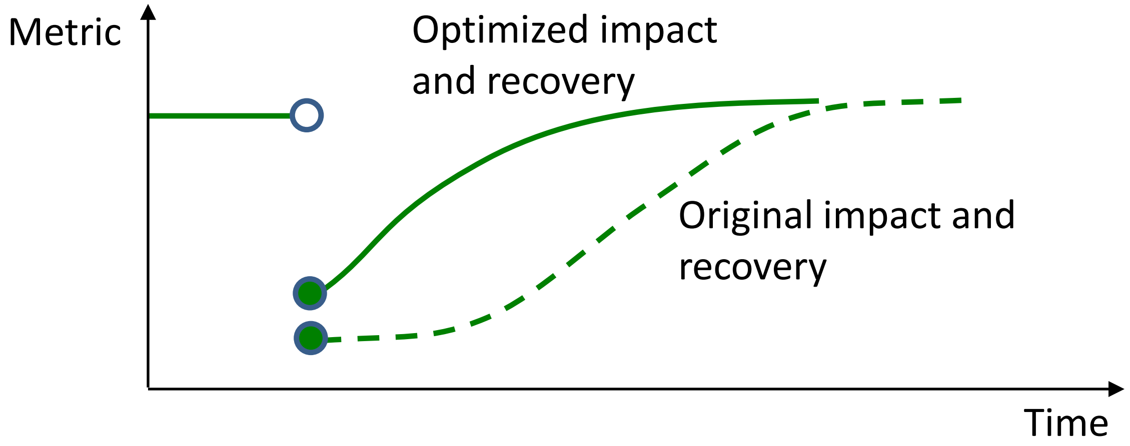
- The methodology allows us to update the model parameters $\mathbf{\Theta}$ in the lower level nested models considering different data types as they become available



Guidotti, R. Cavalieri, F., Gardoni, P., and Franchin, P. (2019). "Bayesian updating of hazard and vulnerability models for regional risk analysis using spatio-temporally distributed heterogeneous data," ASCE Journal of Structural Engineering (under review).

Decision and optimization

- The characteristics of the physical infrastructure, and of the social and economic systems that can be used to modify the hazard impact are used in IN-CORE as levers in an optimization process (Sharma et al. 2019a,b) targeted at
  - reducing the vulnerability of a community by prior planning
  - accelerating the community's recovery following a hazard event



Sharma, N., Tabandeh, A. and Gardoni, P. (2019) "Regional resilience analysis: A multi-scale approach to model the recovery of interdependent infrastructure," In Gardoni, P. (Ed.) *Routledge Handbook of Sustainable and Resilient Infrastructure*, Routledge.

Sharma, N., Tabandeh, A., and Gardoni, P. (2019). "A multi-scale approach to optimize the recovery of interdependent infrastructure," *Computer-Aided Civil and Infrastructure Engineering* (under review).

Testbeds and model validation using hindcasting

Testbeds

- **During the development of IN-CORE, we developed four testbeds (Centerville, Seaside OR, Memphis Metropolitan Statistical Area, Houston/Galveston)** to allow us to test and explore the developed algorithms related to community resilience
- **These four testbeds will be included in IN-CORE for researchers to learn, expand upon, and validate their own algorithms as they expand IN-CORE**

Hindcasting

- **Sector and community models are being validated by comparing modeling results to field data from selected past events** and through sensitivity studies to examine parameters such as event sequence and interdependencies affecting the outcomes of community resilience

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A few concluding remarks

- The National Institute of Standards and Technology (NIST) funded the multi-university five-year Center of Excellence for Risk-Based Community Resilience Planning (CoE) to develop the measurement science to support community resilience assessment
- The developed measurement science is being implemented in a computational environment (IN-CORE) with fully integrated supporting databases to
  - model the impact of natural hazards on communities including recovery,
  - evaluate the key attributes that make communities resilient, and
  - optimize resilience enhancement and planning strategies
- This presentation described some of the key features of IN-CORE

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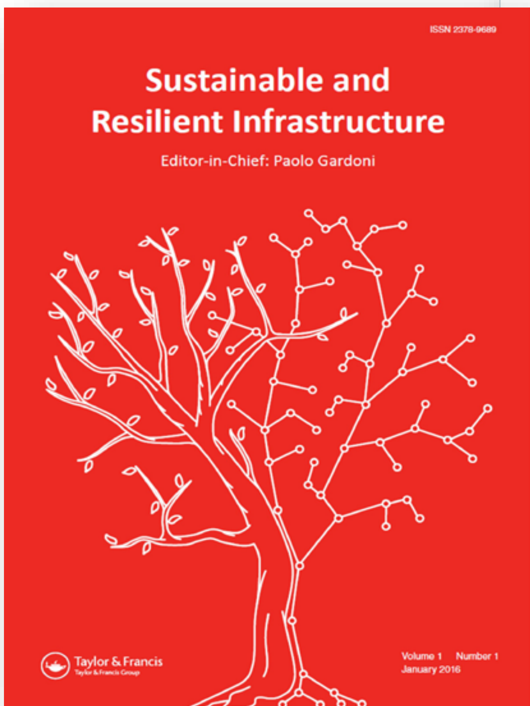
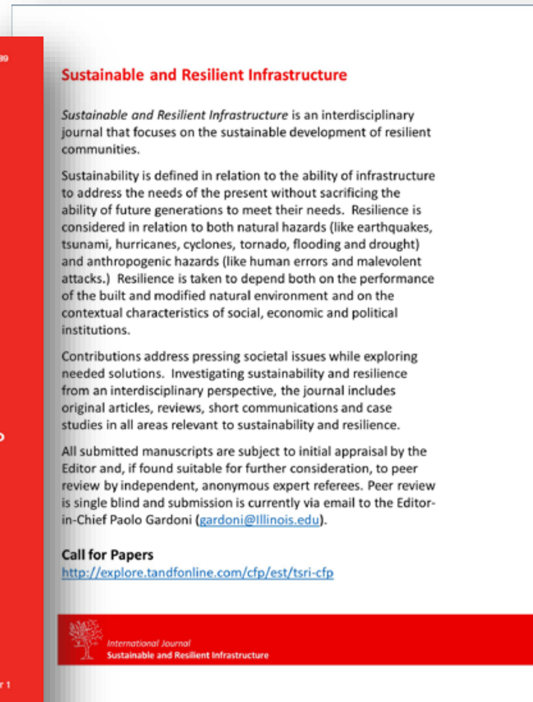
There is a special issue on the modeling of the Centerville Virtual Community using IN-CORE





Sustainable and Resilient Infrastructure

Sustainable and Resilient Infrastructure is an interdisciplinary journal that focuses on the sustainable development of resilient communities.

Sustainability is defined in relation to the ability of infrastructure to address the needs of the present without sacrificing the ability of future generations to meet their needs. Resilience is considered in relation to both natural hazards (like earthquakes, tsunami, hurricanes, cyclones, tornado, flooding and drought) and anthropogenic hazards (like human errors and malevolent attacks.) Resilience is taken to depend both on the performance of the built and modified natural environment and on the contextual characteristics of social, economic and political institutions.

Contributions address pressing societal issues while exploring needed solutions. Investigating sustainability and resilience from an interdisciplinary perspective, the journal includes original articles, reviews, short communications and case studies in all areas relevant to sustainability and resilience.

All submitted manuscripts are subject to initial appraisal by the Editor and, if found suitable for further consideration, to peer review by independent, anonymous expert referees. Peer review is single blind and submission is currently via email to the Editor-in-Chief Paolo Gardoni (gardoni@illinois.edu).

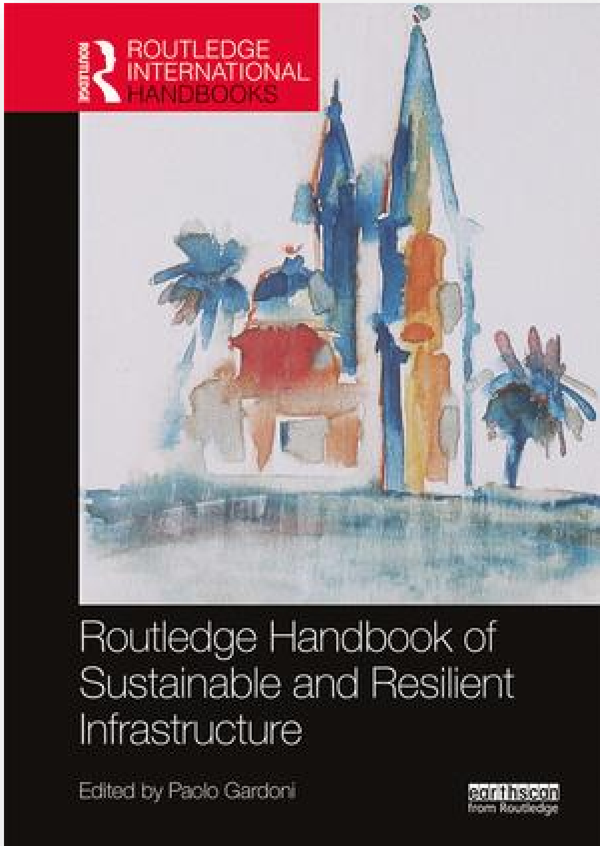
Call for Papers
http://explore.tandfonline.com/cfp/est/tsri-cfp

International Journal
Sustainable and Resilient Infrastructure

Sustainable and Resilient Infrastructure (SRI) is an interdisciplinary journal that focuses on the sustainable development of resilient communities.

Special Issue in *Sustainable and Resilient Infrastructure* (published by Taylor & Francis as Vol. 1, Issue 3-4, December, 2016)
http://www.tandfonline.com/loi/tsri

There is handbook on Sustainable and Resilient Infrastructure that includes Center’s research



Routledge Handbook of Sustainable and Resilient Infrastructure

"This book collects articles by well-known experts on sustainability and resilience of infrastructure systems in the face of natural hazards, including climate change, and aging. It is a must read for anyone researching or practicing in this field."
— *Armen Der Kiureghian, President, American University of Armenia and Taisei Professor of Civil Engineering Emeritus, University of California, USA*

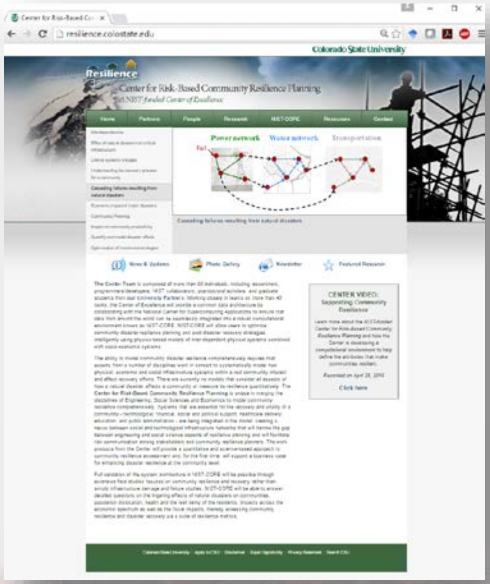
"This truly comprehensive compendium on theories and applications of resilience for the built environment is highly recommended for those seeking a comprehensive understanding of the issues […]."
— *Ross B. Corotis, Denver Business Challenge Professor of Engineering, University of Colorado, USA*

"Edited by one of the leading scholars in the field, the *Routledge Handbook of Sustainable and Resilient Infrastructure* provides an authoritative and comprehensive overview of the state-of-the-art. Essential reading for both professionals, students, and scholars working on the nexus between sustainability and resilience."
— *Neelke Doorn, Professor Ethics of Water Engineering, Delft University of Technology, The Netherlands*

Gardoni, P. (Ed.) (2019) *Routledge Handbook of Sustainable and Resilient Infrastructure*, Routledge.

Other resources

The 2018 EMI Objective Resilience Lecture
“Promoting societal well-being by designing sustainable and resilient infrastructure: engineering tools and broader interdisciplinary considerations”
URL: https://www.asce.org/engineering-mechanics/objective-resilience-lecture/



Center of Excellence Website
URL: http://resilience.colostate.edu
Email: resilience@colostate.edu

Thank you!

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Resilience