Measuring Lifeline Emergency Response using temporal network models

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My research team:

- Paolo Fantini
- Fabiana Barberis
- Sebastiano Marasco, Ph.D. candidate
- Marzia Malavisi
- Marta Pique`
- Alessio Vallero
- Alba Chiara Trozzo
- Sarah Moretti
- Vincenzo Arcidiacono, PhD.
...Disasters in the world

Terremoto l’Aquila 6 Aprile, 2014

Earthquake + Tsunami, 11 Marzo 2011

Crollo del Takoma Bridge, 1940

Genova 9 Ottobre 2014
Natural disasters reported 1900-2013

Average annual damages ($US billion) caused by reported natural disasters 1990 - 2011
...from “Knowing”, 2009
“Our greatest glory is not in never falling, but in always recover after a fall. “

Confucio
Resilience

The term resilience derives from the latin word “resilio” (da re e salio) which means bounce back, but also not being touch by something (of negative).
Disaster Resilience
Unique decision variable (DV)

• Resilience: normalized function indicating the capacity to maintain a certain level of functionality or performance in a given building, bridge, lifeline, network for a given period $T_{LC}$ (life cycle, etc.) including the post-disaster recovery time [Cimellaro et al., 2006].

$$R_i = \frac{\int_{0}^{T_{LC}} \left( \frac{Q_i(t)}{T_{LC}} \right) dt}{0 \leq R_i \leq 1}$$

$0 < R < 1$
Resilience of Building structures

- Performance requirements
- Observations on past earthquakes
- Laboratory Experiments

- Scenario Events (e.g., PSHA, a, pga, Tr)

- System Model (Building, Structure etc.)

- System Response (e.g. drift, acc, base shear)

- Fragility analysis

- Performance Limit State

- Intensity measures (I) (PGA, PGV, Return Period, Sa, Sv, Sd, …)

- Response parameters (R) (Interstory drift, absolute acceleration, Force, …)

- Recovery Evaluation Model (e.g. Tre, Rec. Function)

- Loss Evaluation Model L (Losses, Casualties)

- Functionality $Q_{TOT}$

- Resilience R (%)

- Decision support system

- Advanced technologies (e.g. Base isolation, viscous dampers, etc.)

- Remedial Mitigation actions
- Remedial Resilience actions

- Robustness
- Rapidity
- Resourcefulness
- Redundancy
Community Resilience Evaluation

Disruptive Event (Scenario analysis)

Community Hybrid model

Performance measures

Calibration

DATA (Real, Simulated)

Robustness

Rapidity

Resourcefulness

Redundancy

Resource & Opportunity Evaluation

Gaps & Priority Identification

Decision support system

No

Yes

Community Resilience index

High Resilience

Low Resilience

Social-Cultural Capital

Organized governmental services

Economic Development

Physical Infrastructures

Lifestyle and Community Competence

Population/Demographic

Environmental/Ecosystems

Resilience Performance levels

Validation and verification

Performance measures

Community Resilience Evaluation

Disruptive Event

(Scenario analysis)

Community Hybrid model

DATA

(Real, Simulated)
Dimensions of Community Resilience

- **POPULATION AND DEMOGRAPHICS**
  - Composition, Distribution, Socio-Economic Status, etc.

- **ENVIRONMENTAL/ECOSYSTEM**
  - Air quality, Soil, Biomass, Biodiversity, etc.

- **ORGANIZED GOVERNMENTAL SERVICES**
  - Legal and security services, Hygiene and health services, etc.

- **PHYSICAL INFRASTRUCTURE**
  - Facilities, Lifelines, etc.

- **LIFESTYLE AND COMMUNITY COMPETENCE**
  - Quality of Life, etc.

- **ECONOMIC DEVELOPMENT**
  - Financial, Production, Employment distribution, etc.

- **SOCIAL-CULTURAL CAPITAL**
  - Education services, Child and elderly care services, etc.
IDEal reSCUE - VISION

Project Goal
To develop a novel method to assess the performance of critical infrastructures and their interdependencies while taking into account the influence of human behavior and its emotions.

Gaps in Science
1. A comprehensive model of a metropolitan area while considering all infrastructures and their interactions is missing.

2. Modeling the human behavior within the context of infrastructure interdependencies using ABMS is not available.

Multidisciplinary interdisciplinary skills of Engineers, Social Scientists, software developers.
IDEal reSCUE - IMPACT

Scientific/Engineering

- New techno-socio-economic models (feasible within the next 10-15 years).
- Open a new field of research in Hybrid modeling combining the potentialities of Network and agent-based models.
- The project will answer some of the “open questions” on temporal networks.
- Different models of infrastructures (virtual 3D) will be linked in a decision making tool.

Social

- Improve resiliency of civil infrastructures after extreme events.
- Aid infrastructure asset managers during emergency situations;
- The model will be used for TRAINING and EDUCATION purposes;
- New techno-socio-economic models (feasible within the next 10-15 years).
- Open a new field of research in Hybrid modeling combining the potentialities of Network and agent-based models.
- The project will answer some of the “open questions” on temporal networks.
- Different models of infrastructures (virtual 3D) will be linked in a decision making tool.
Outline

- Framework to evaluate community resilience;

- Applications on Resilience of Building structures;
  - Hospital/school building;
  - Emergency Department;

- Applications on Resilience of infrastructures;
  - Water distribution network;
  - Natural Gas distribution network;
  - Infrastructure interdependencies at different spatial scales (local vs. global level);
  - Economic Resilience of a community (e.g. the Bay area case study);
  - Emergency damage assessment using Smart phones;
  - Evacuation plan from a museum;
General framework

DEGREE OF INTERDEPENDENCY

Type of interdependency

Physical

Cyber

Geographical

Policy/Procedural

Societal

Budgetary

Market & Economy

Type of Failure

Coupled

Cascading

Amplification

Uncoupled
Degree of interdependency
Infrastructure level

- The values are located in a community interdependency matrix.

<table>
<thead>
<tr>
<th></th>
<th>Electricity</th>
<th>Oil delivery</th>
<th>Transportation</th>
<th>Telecommunication</th>
<th>Natural Gas delivery</th>
<th>Water supply</th>
<th>Wastewater treatment</th>
<th>Financial system</th>
<th>Building services</th>
<th>Business</th>
<th>Emergency services</th>
<th>Food supply</th>
<th>Government</th>
<th>Health care</th>
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</table>

Index of subordination (dependence) | 6.4 | 6.8 | 8.4 | 5.6 | 7.1 | 6.5 | 4.6 | 11.6 | 8.0 | 12.9 | 10.5 | 10.5 | 13.0 | 7.8 | 5.0 | 8.8 |
The proposed analytical method uses the restoration curves (or functionality curves) to evaluate the index of interdependency.
The available data correspond to 12 regions in Japan for 3 types of infrastructure (Power, water and gas distribution network);

Logarithmic transformation and double differentiation of the series;

Evaluation of the cross correlation function \( \rho(h) \) for each couple of transformed functionality curves
Regional Resilience index
Weight Coefficients

- The weight of each infrastructure \((w_i)\) in every region is evaluated starting from the matrix of interdependency \((S_{ij})\) evaluated using the following formula:

\[
  w_i = \frac{\sigma_i}{\sum_i \sigma_i}
\]

where

\[
  \sigma_i = \sum_j S_{i,j} \quad \text{when} \quad S_{i,j} > 0
\]
The resilience assessment of a single infrastructure ($R_i$) is given by the following integral:

$$R_i = \int_0^{T_{LC}} \left( \frac{Q_i(t)}{T_{LC}} \right) dt$$

$$0 \leq R_i \leq 1$$

The global resilience of a given region ($R$) can be evaluated through the weight average of the resilience index of each infrastructure of the region at hand:

$$R = \sum_i (R_i \times w_i)$$
Case study: Tohoku earthquake
Global regional level

$0 \leq R \leq 1$
Regional Resilience indices

Regional Resilience with different weights

- Kanagawa
- Saitama
- Gunma
- Chiba
- Aomori
- Tochigi
- Ibaraki
- Akita
- Yamagata
- Fuhushima
- Iwate
- Miyagi

- Eq. 1 - (Dueñas-Osorio and Kwasinski 2012)
- Eq. 2
- Eq. 3
- Eq. 4
- Same weight
Coupled Resilience

\[ Q(t) \]

Period 1: \[ T_i \]
Period 2: \[ T_1, T_c \]
Asymptotic behaviour
End of the calculation of the Resilience
End of Data Records

\[ R_1 \]
\[ R_2 \]

Time \( t \)
Coupled vs. uncoupled Resilience

**Coupled Resilience**

- Days (a)
- Q(t) [%]
- 1st event
- 2nd event
- Partial recovery

**Uncoupled Resilience**

- Days (b)
- Q(t) [%]
- 1st event
- 2nd event
The restoration curves of a given region are divided according to the period range between two subsequent aftershocks so that the functionality of at least one of the functionality curve has a drop of functionality.
Optimal period range $T_LC$
Evaluation of weight coefficients $w_i$

Four options are possible:

1. Evaluate $w_i$ over the entire control period;
2. Evaluate $w_i$ over the first interval between two aftershocks (Period A);
3. Evaluate $w_i$ separately over all the intervals (Exact method);
4. Assume $w_i$ equal and constant for all infrastructures;
The proposed **exact method** for the resilience assessment of a given region is given by the following equation:

\[
R = \frac{1}{T_{le}} \left\{ \sum_{i} \left[ \int_{T_{0}}^{T_{i}} Q_i(t) dt \cdot w_{i,(0)} \right] + \ldots + \sum_{i} \left[ \int_{T_{n-1}}^{T_{n}} Q_i(t) dt \cdot w_{i,(n-1)} \right] + \sum_{i} \left[ \int_{T_{n}}^{T_{le}} Q_i(t) dt \cdot w_{i,(n)} \right] \right\}
\]

Some considerations can be added introducing the concept of coupled and uncoupled resilience;
Optimal period range for the weight coefficient assessment $w_i$

1. Assume $w_i$ equal and constant for all infrastructures;
2. Evaluate $w_i$ over the first interval between two aftershocks (Period A);
3. Evaluate $w_i$ separately over all the intervals (Exact method);
Regional resilience

Regional resilience index

0.0 0.2 0.4 0.6 0.8 1.0 1.2

Miyagi
Iwate
Fukushima
Ibaraki
Ibaraki
Chiba
Yamagata
Aomori
Akita
Tochigi
Gunma
Saitama
Kanagawa

Coupled
Uncoupled

R_{W_{i}(A)}
R_{Eq.(7)}

Resilience
MEASURING LIFELINE EMERGENCY RESPONSE USING TEMPORAL NETWORK MODELS

Paolo Fantini¹, Gian Paolo Cimellaro², Stephen Mahin³

1: Visiting student researcher at PEER
2: Visiting professor at UC Berkeley
3: Professor at UC Berkeley
# Motivations

Exploring new types of network models for modeling lifelines during emergencies

| Why this research is important | - Governments consider lifelines resilience a **priority**  
| - A good management of emergency response phase can limit **cascading effects** and damages. |
| Criticalities | Many models, like the IIM (Haimes and Jiang, 2001), attempt to simulate lifelines interdependence, but **temporal effects** can modify the topology of the system and invalidate their results. |
| Possible integrations | Studies of **dynamic networks** in fields like telecommunication engineering, social science, artificial intelligence can be applied in the risk management of critical infrastructure systems. |
| Our hypothesis | Implementing the IIM with a **probabilistic** and **multilayer** approach and introducing a **tensor** notation, which takes into account the time variable, is effective for obtaining more realistic emergency scenarios. |
Graph theory

Lifelines can be model using graph theory where the network is modeled using: source node, sink node, oriented edge, chain, adjacency matrix.
The Input-output Inoperability Method (IIM)

Developed by Haines and Jiang (2001) is a model for determining the propagation of the probability of inoperability in infrastructure systems. Its fundamental equation is:

\[ q = [I - A]^{-1} \cdot c \]

- \( c \) (scenario vector): perturbation introduced in the systems;
- \( A \) (interdependency matrix): describes the topology of the systems;
- \( q \) (damage vector): result of the propagation of the perturbation.
# Limitations of IIM and suggested implementations

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<thead>
<tr>
<th>Limitations</th>
<th>Implementations</th>
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<td>- Does not model the advantages of having redundancies in the systems.</td>
<td>① Introduction of probabilistic quantities and step by step calculation of propagation effects.</td>
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<td>- Difficulties in modeling interdependencies between different networks;</td>
<td>② Model different infrastructures with interconnected layers.</td>
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<td>- Static model that does not consider the evolution of the system;</td>
<td>③ Give a time dimension to the model by modeling the topology change with a tensor notation.</td>
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<td>- Not accounting the temporal effects that can disrupt the systems.</td>
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</table>
The proposed model shift from the \( c \) and \( q \) vector of the IIM to probabilistic quantities.

**Input**
- Event vector \( E \) (Natural Hazard)
- Fragility curves (Vulnerability)

**Output**
- Prob. of self-failure \( P_{sf} \) (from \( E \) vector and Fragility curves)
- Prob. of cascading failure \( P_{cf} \) (propagation of upstream \( P_{sf} \) computed step by step)
- Prob. of failure \( P_f \) (combination of \( P_{sf} \) and \( P_{cf} \))
① Probabilistic formulation

Flowchart to determine the probability of failure $P_f$
# Limitations of IIM and suggested implementations

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Multilayer approach for spatial interdependency

Different infrastructures can be modeled like separate layers of the same system. Interdependent nodes are projected on different layers and establish links between them.
Multilayer approach for spatial interdependency

Every infrastructure is considered as a separate network described by its *adjacency matrix*:

\[
A_i = \begin{bmatrix}
(a_{11})_i & \cdots & (a_{1n})_i \\
\vdots & \ddots & \vdots \\
(a_{n1})_i & \cdots & (a_{nn})_i
\end{bmatrix}, \quad A_j = \begin{bmatrix}
(a_{11})_j & \cdots & (a_{1m})_j \\
\vdots & \ddots & \vdots \\
(a_{m1})_j & \cdots & (a_{mm})_j
\end{bmatrix}, \quad \ldots
\]

To take into account interdependencies, *inter-network matrixes* are introduced:

\[
I_{j \rightarrow i} = \begin{bmatrix}
(i_{11})_{j \rightarrow i} & \cdots & (i_{1n})_{j \rightarrow i} \\
\vdots & \ddots & \vdots \\
(i_{m1})_{j \rightarrow i} & \cdots & (i_{nn})_{j \rightarrow i}
\end{bmatrix}, \quad \ldots
\]

*Cascading effects* are evaluated transferring the *probability of failure* from the upstream network (here it is \(j\)) to the dependent one (here it is \(i\)):

\[
P^*_{sf_i} = (I_{j \rightarrow i}^T \cdot P_{cf_i}) \cup P_{sf_i}
\]
Limitation of IIM and suggested implementations

Limitations

- Does not model the advantages of having redundancies in the systems.
- Difficulties in modeling interdependencies between different networks;
- Static model that does not consider the evolution of the system;
- Not accounting the temporal effects that can disrupt the system.

Implementations

1. Introduction of probabilistic quantities and step by step calculation of propagation effects.
2. Model different infrastructures with interconnected layers.
3. Give a time dimension to the model by modeling the topology change with a tensor notation.
Tensor notation for accounting temporal effects

Probability of failure of nodes, and thus the topology of the system, can change over time.
Being the lifelines critical and strategic infrastructures, they are designed to work also in unfavorable conditions. The flow from source nodes to sink nodes can follow different paths (chains), characterized by an hierarchy position:

- Main supply line (1st in hierarchy)
- First back-up line (2nd in hierarchy)
- Second back-up line (3rd in hierarchy)
- ...

These separate paths are considered mutually exclusive, so they are operative at different time.
Tensor notation for accounting temporal effects

To model the presence of different configurations at different time steps, the *adjacency tensor* $A(t)$ is introduced.
Tensor notation for accounting temporal effects

Case study – Adjacency tensor of a Nuclear Power plant cooling water network
Tensor notation for accounting temporal effects

One configuration is active if its nodes do not fail and if configurations with higher hierarchy position are not activated. Knowing the probability of failure of each node of each configuration, it is possible to determine the probability that a configuration is active.

This probability is represented by the *Operability Label* \(L_{\text{op}}\) and is associated to every layer of the *adjacency tensor*. It can vary over time due to disruptive events or simply aging.

- The value \(1-\sum L_{\text{op}}\) describes the probability that none of the possible configurations is active, and so corresponds to the *loss of capacity* of the system;

- Knowing when a back-up line is kicked off and for how long it is active, allows to *quantify the temporal effects* (e.g. the run out of autonomy of diesel tank serving a UPS).
Tensor notation for accounting temporal effects

Example
Concluding remarks

The proposed model is able to:

a) Evaluate the cascading effects generated by interdependencies using a multilayer approach (e.g. GIS platform)

b) take into account the temporal effects and the represent the evolution of the emergency response.

c) measure the robustness of an infrastructure system;
Outline

- Framework to evaluate community resilience;
- Applications on Resilience of Building structures;
  - Hospital/school building;
  - Emergency Department;
- Applications on Resilience of infrastructures;
  - Water distribution network;
  - Natural Gas distribution network;
  - Infrastructure interdependencies at different spatial scales (local vs. global level);
  - Economic Resilience of a community (e.g. the Bay area case study);
  - Emergency damage assessment using Smart phones;
  - Evacuation plan from a museum;
# AeDES Survey Form

The AeDES survey form is composed by 9 sections:

1. **Building identification**
2. **Building description**
3. **Typology**
4. **Damage to structural elements and short term countermeasures carried out**
5. **Damage to non structural elements and short term countermeasures carried out**
6. **External damage due to other constructions and short term countermeasures carried out**
7. **Soil and foundations**
8. **Usability judgment**
9. **Other observations**
Users Residents Mode
Damage assessment for non expert users

![Digitalized signature](image.png)
Professional Mode (ATC-20)
Damage assessment for expert users
Professional Mode (AeDES)
Damage assessment for expert users
EDAM - Earthquakes Damage Assessments Manager

- Automatic localization (For now, Italian and English);
- Available for iOS and Android phones and tablets;
- Subsequently on Blackberry and Windows Phone based devices;
- Tested during the emergency response of South Napa earthquake for 20 citizens’ buildings.

Create new forms

- Fill all the required fields in a fast and intuitive way
- Voice commands to fill text fields

Multimedia data

Take pictures and record video with:
- Geolocalization
- Damaged area (%) and level (1-5)

Make a detailed collage about damages

Create personal drafts
And then...

It is possible to create .PDF files automatically populated with entered data (including multimedia contents) and send it by email.

And synchronize the forms on EDAM’s server

Source:
http://recursostic.educacion.es/observatorio/web/images/upload/1observatorio/iconos_art/pdf.png
Maximum security

- HTTPS protocol;
- Password stored after salted SHA-512 elaboration;
- Session that expire after 30 minutes of inactivity;
- Encrypted data in the mobile phone.

Source: http://rjwestmore.com/wp-content/uploads/2013/02/Smartphone2-Corp.jpg
Test of EDAM at Napa (California)

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Computational Methods, Seismic Protection, Hybrid Testing and Resilience in Earthquake Engineering

A Tribute to the Research Contributions of Prof. Andrei Reinhorn

Springer
Thank You!

Questions?
References


