POLITECNICO
MILANO 1863
DIPARTIMENTO DI ENERGIA

Risk Assessment and Management of Interdependent Critical Infrastructures

Maria Valentina Clavijo Mesa

Agenda

1. Interdependencies between Critical Infrastructures

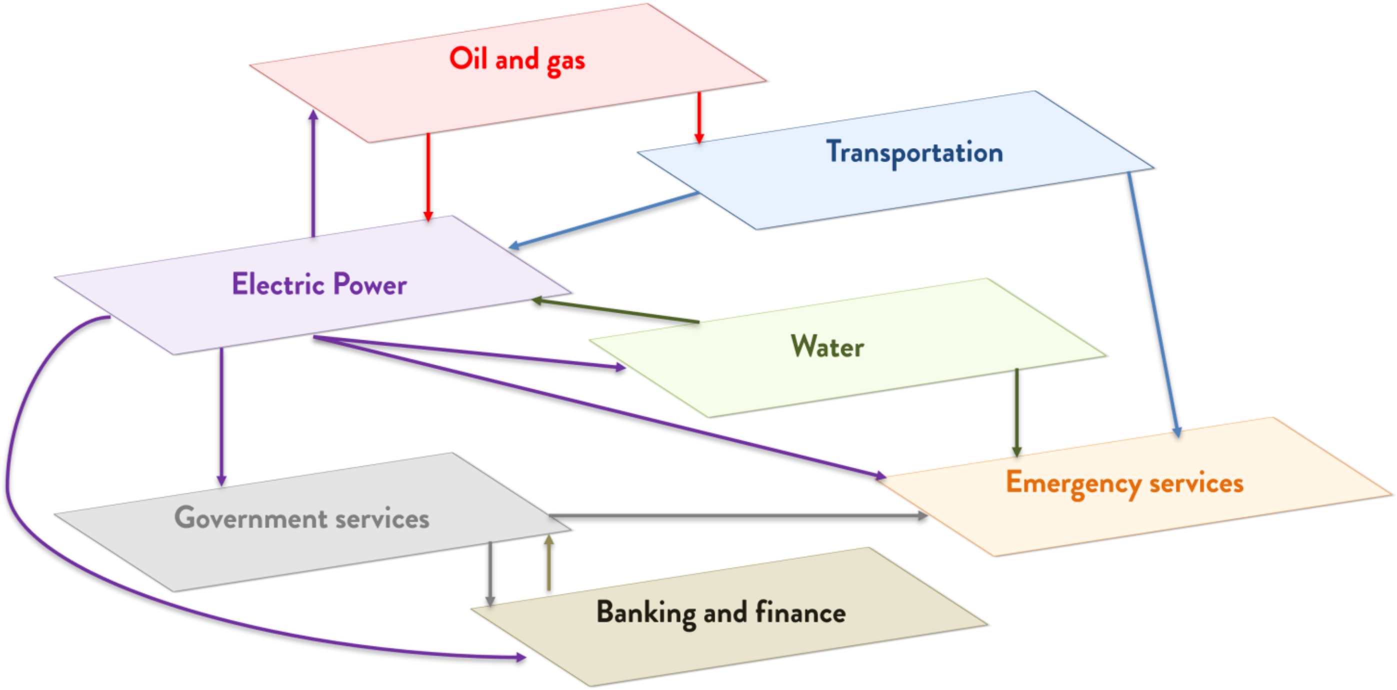
    1.1 Why Model Interdependencies?
    1.2 Approaches Available to Model Interdependencies

2. Hybrid Approach to Model Interdependencies

    2.1 Economic Theory-based Model: DIIM
    2.2 Multi-state DIIM

3. Exam Preparation Exercises

1.1 Why Model Interdependencies?



Critical Infrastructures describes assets that are essential for the functioning of a society and economy [1]

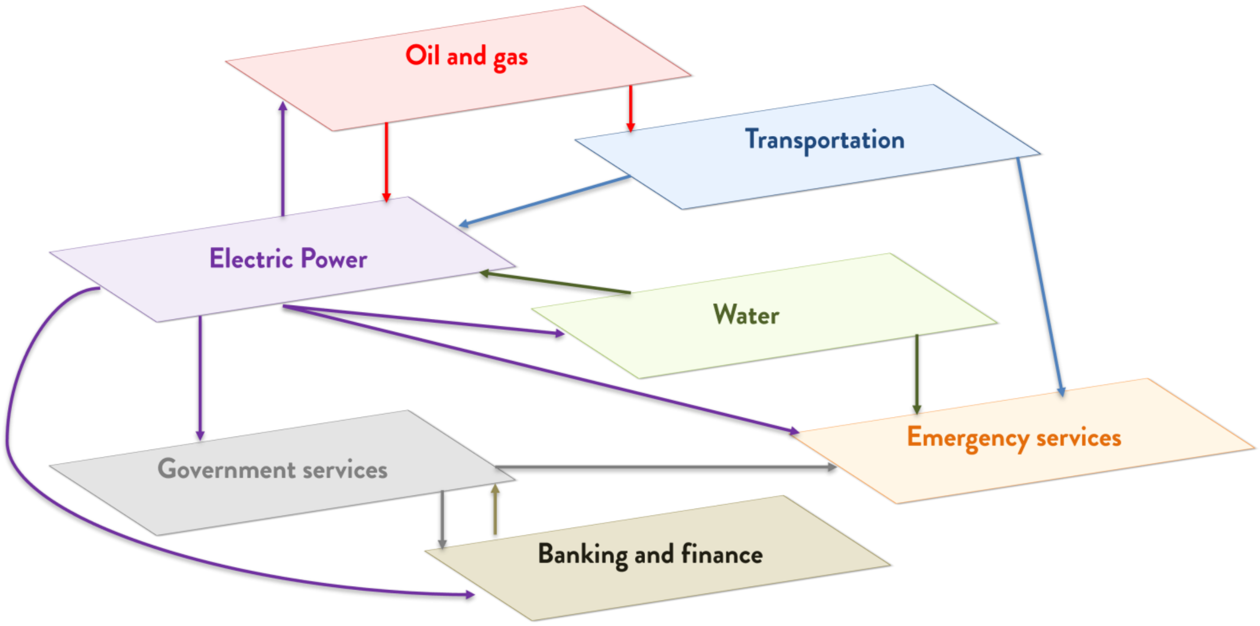
- By 2030, **60%** of the world's population will live in urban areas,
- This growth creates **technical and economic challenges** for CIs **owners** and **systems of systems planners**,
- Future cities will strain current safety and security engineering models
- New and complex **cascading failure** modes will emerge due to unforeseen system behaviours

[2]

1. Interdependencies between Critical Infrastructures

1.1 Why Model Interdependencies?

In an **interconnected** world, **hidden interdependencies** between infrastructures often **become evident during hazard events**, making it crucial to model them to understand vulnerabilities and ensure resilience



The Great Texas Freeze [3]

The *2021 Texas Winter Storm* caused power grid failures, disrupting water and gas systems, affecting **5.2 million homes**, with damages reaching ***$195 billion*** and *over 700 fatalities*

Rio Grande do Sul, Brazil floods response [4]

In early *2024, Southern Brazil* was hit by extratropical cyclones and flooding after a dam collapse, affecting *28.8 million people* and causing *$20.4 billion* in damages, with power outages in the region, road closure, and airport shutdowns

1. Interdependencies between Critical Infrastructures

1.1 Why Model Interdependencies?

A **dependency** is a *unidirectional relationship* in which the functioning of one infrastructure is influenced by another

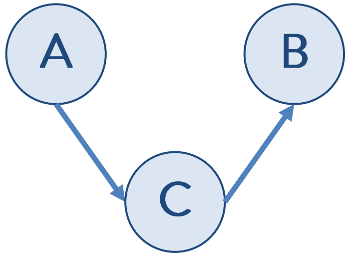
An **interdependency** is a *bidirectional relationship* in which two or more infrastructures mutually influence each other's state

Dependencies between two infrastructures may be **direct** or **indirect:**

First order dependency

B depends directly on A

Second order dependency



B depends on A through another infrastructure C

[5]

1.1 Why Model Interdependencies?

Water infrastructure

Health infrastructure

Power infrastructure

- P→W: Pumping system,
- W→P: Cooling systems,
- W→H: Sanitation & operation

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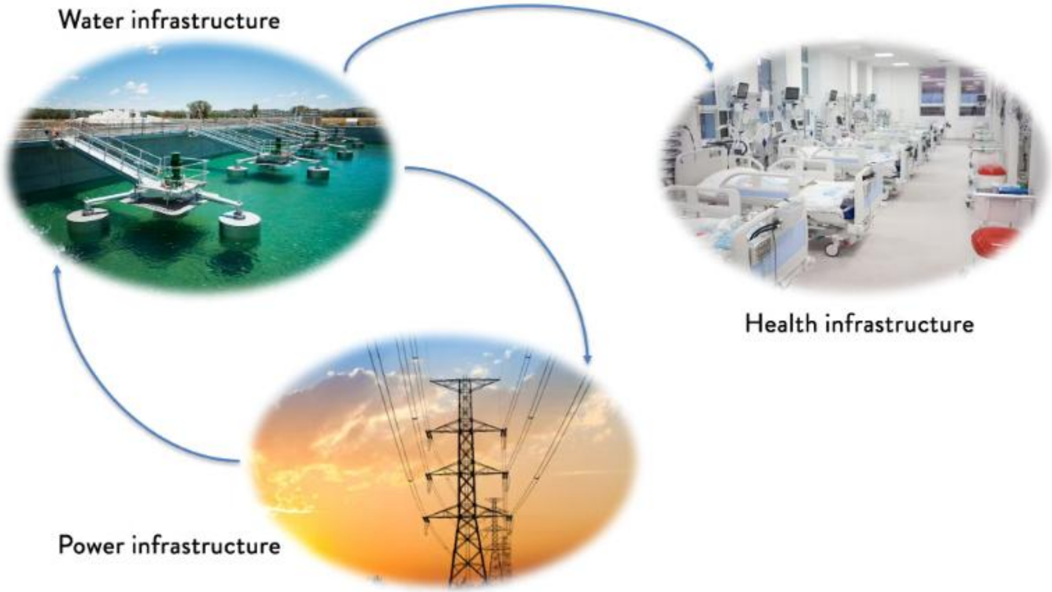
Understanding Infrastructure Dependencies



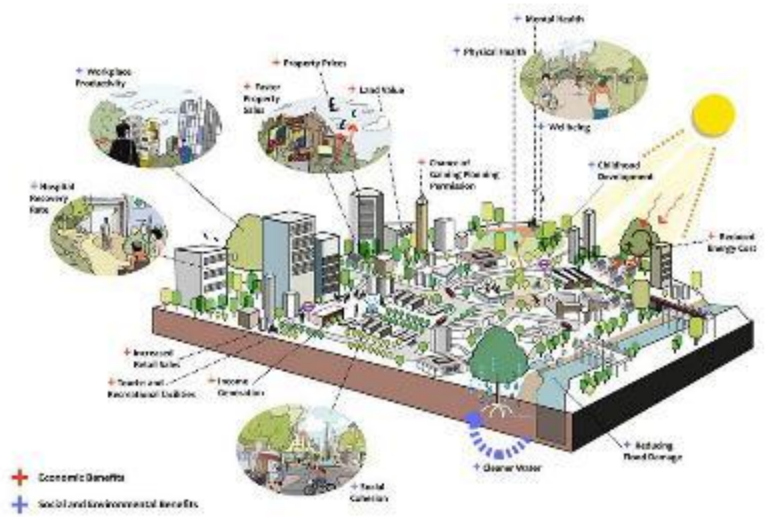
The interdependency literature adopts **different** planning horizons

System-of-Systems Planner

Owner or Operator of an infrastructure

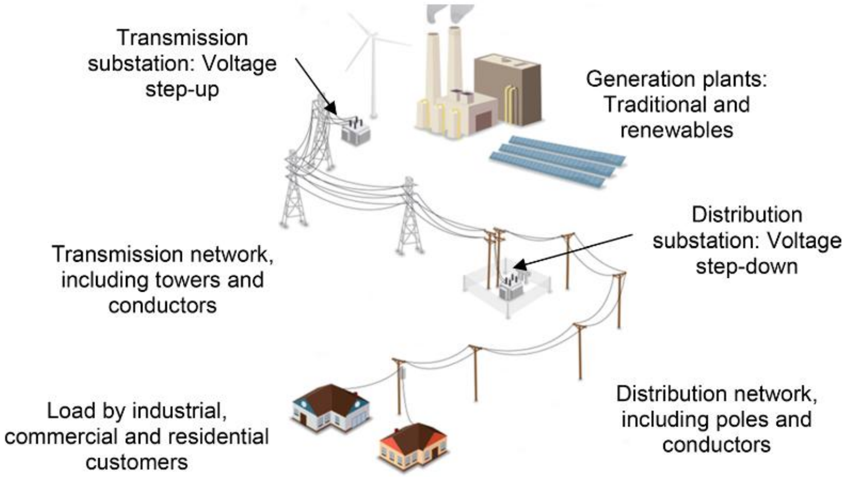
[6]

The interdependency literature adopts **different** planning horizons



System-of-Systems Planner

- *What are the expected **economic losses** of an extreme event in the region?*
- *Which is the **most critical industry** in terms of inoperability?*
- *How can we **expand networks** to introduce redundancies in the most vulnerable locations?*



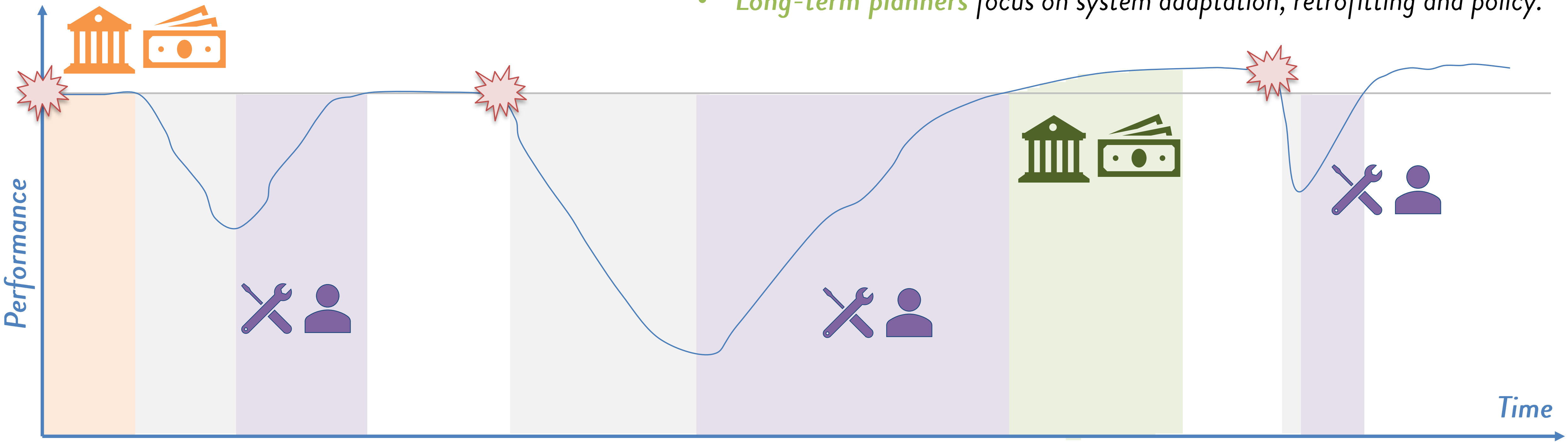
Owner or Operator of an infrastructure

- *What is the **change in resilience** of my CI when adding a security barrier?*
- *What is the **expected cost** of adding a security barrier?*

[6]

Resilience trajectories are shaped by multiple decision-makers across different timescales

- *The performance trajectory evolves through anticipation, absorption, recovery and adaptation.*
- *Resilience phases depend on decision made by different actors.*
- *Short-term operators focus on immediate restoration and continuity.*
- *Long-term planners focus on system adaptation, retrofitting and policy.*

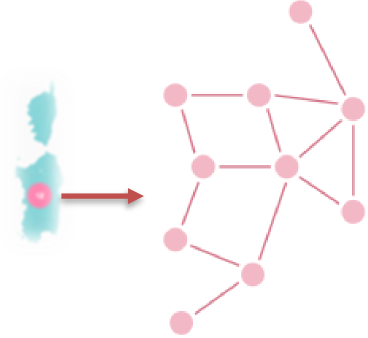


1. Interdependencies between Critical Infrastructures

1.1 Why Model Interdependencies?

Interdependency between CIs

Holistic approaches provide strategic insights for system-of-systems planners



Reductionist approaches provide information to system operators for optimizing infrastructure layout, safety measures, and resilience within a CI

[7]

1.1 Why Model Interdependencies? - References

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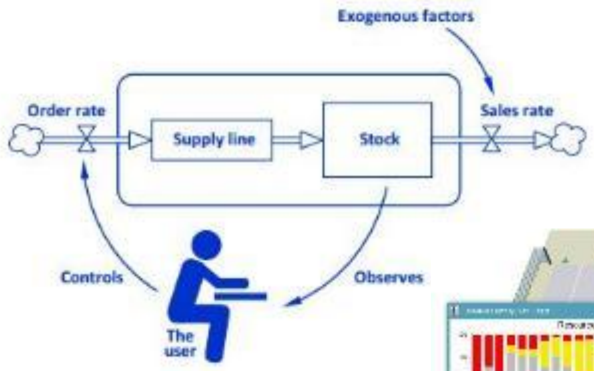
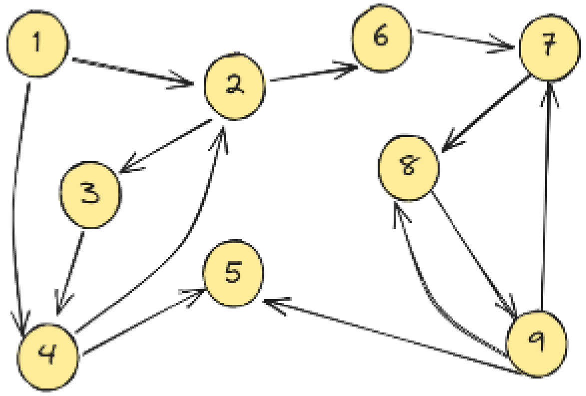
1.2 Approaches Available to Model Interdependencies





1. Interdependencies between Critical Infrastructures

1.2 Approaches Available to Model Interdependencies

Models can be classified into **two main categories** based on **how they capture** dependencies and interdependencies

Interdependency models

1. Holistic Approaches

A holistic approach models each CI as a ***whole system*** and uses ***simplified representations*** to capture how it depends on services from other CIs

2. Reductionist Approaches

A reductionist approach ***breaks down CIs*** into their components, analyzing how the system evolves based on the ***behavior and interactions of these parts***

[1]

1. Holistic Approaches

1.1 Survey-based table

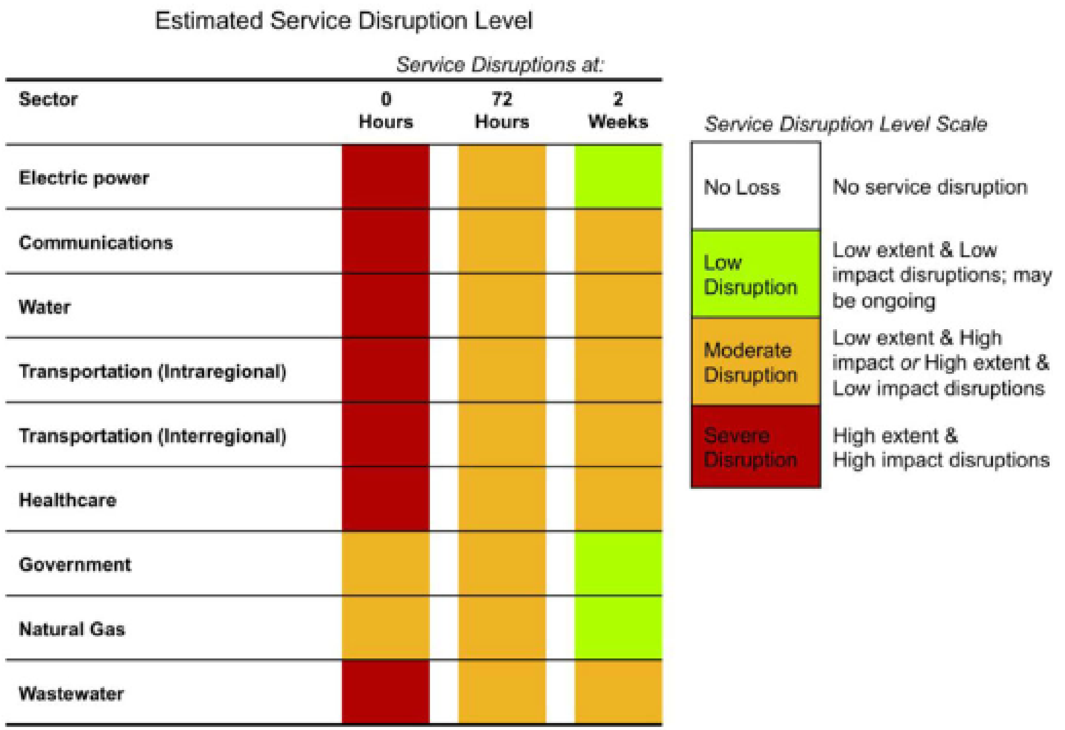
*This involves collecting **expert opinion** through surveys to assess dependencies and interdependencies between CIs.*

The representation of interdependency is simple and intuitive

Results are specific to the surveyed event and community

Toward Disaster-Resilient Cities: Characterizing Resilience of Infrastructure Systems with Expert Judgments

Stephanie E. Chang, Timothy McDaniels, Jana Fox, Rajan Dhariwal, and Holly Longstaff



[2]

1. Holistic Approaches

1.2 Correlation-based table

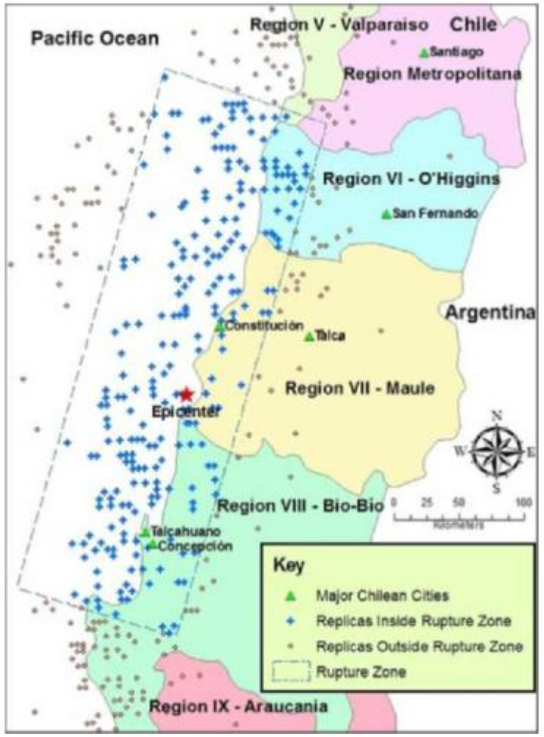
This utilizes correlation coefficients, such as ***Pearson*** *and* ***cross-correlation coefficients****, to quantify how CIs are interconnected, using data on system* ***failures and recovery patterns over time***

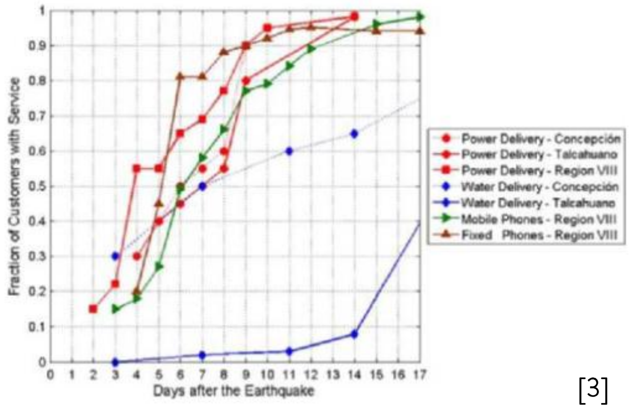
Utilizes statistical coefficients to analyse historical data on failures and recovery

Interpretation requires expert analysis, introducing potential bias

Quantification of Lifeline System Interdependencies after the 27 February 2010 M_W 8.8 Offshore Maule, Chile, Earthquake

Leonardo Dueñas-Osorio, M. EERI, and Alexis Kwasinski





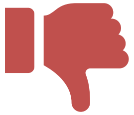
[3]

1. Holistic Approaches

1.3 Economic theory-based models

*These models use **linear equations** to evaluate economic interactions, supporting policy development and disaster planning*

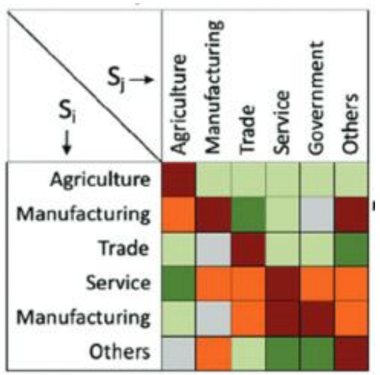
Supports economic policy development and disaster response planning

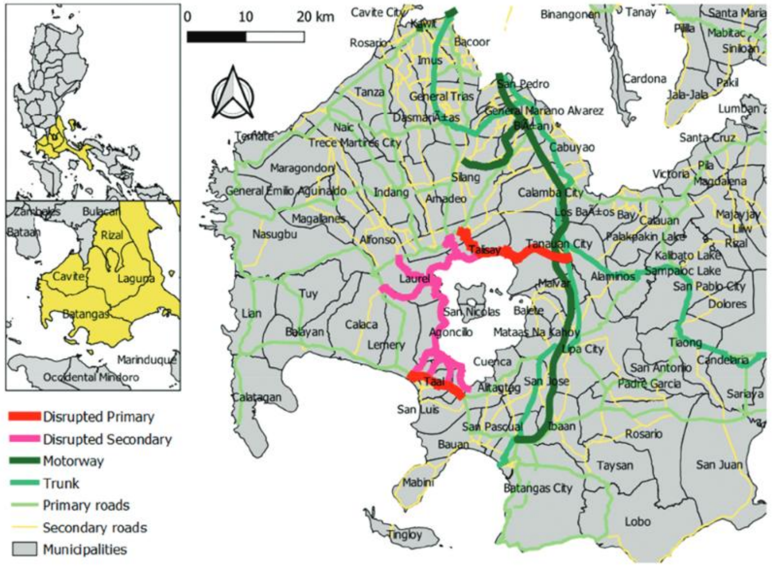


Focuses mainly on economic impacts at the system level

Assessing the economic ripple effects of critical infrastructure failures using the dynamic inoperability input-output model: a case study of the Taal Volcano eruption

Joost Santos[a], Krister Ian Daniel Z. Roquel[b], Albert Lamberte[c], Raymond R. Tan[d], Kathleen B. Aviso[d], John Frederick D. Tapia[d], Christine Alyssa Solis[c] and Krista Danielle S. Yu[c]





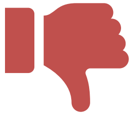
[4]

1. Holistic Approaches

1.4 System dynamics

These models are used to understand the ***nonlinear behavior*** *of complex systems over time, helping to analyze CI interactions and evolution*

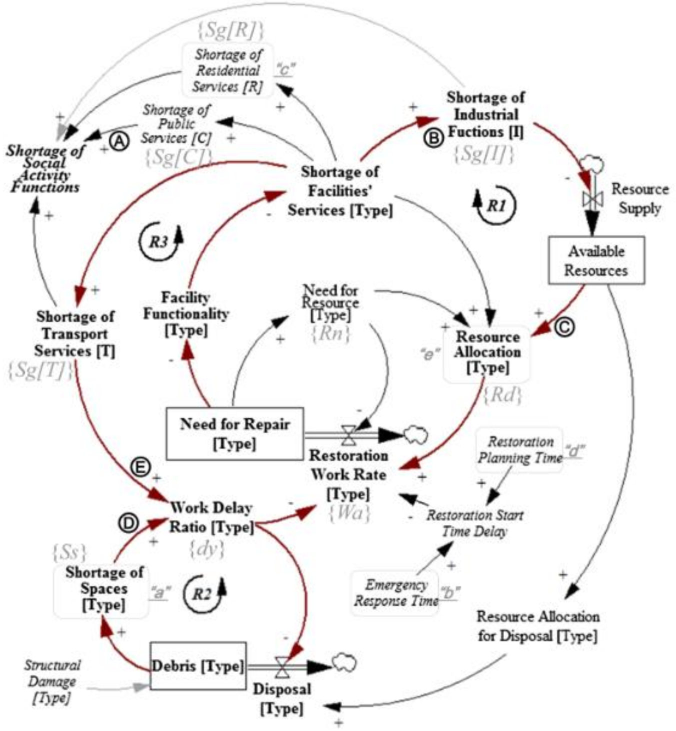
Provides insights into complex systems behaviours over time using causal-loop and stock-flow diagrams



Limited in uncertainty quantification and difficult to validate

Postdisaster Interdependent Built Environment Recovery Efforts and the Effects of Governmental Plans: Case Analysis Using System Dynamics

Sungjoo Hwang, S.M.ASCE[1]; Moonseo Park, A.M.ASCE[2]; Hyun-Soo Lee, A.M.ASCE[3]; SangHyun Lee, M.ASCE[4]; and Hyunsoo Kim, S.M.ASCE[5]



[5]

1. Holistic Approaches

1.5 Data-driven models

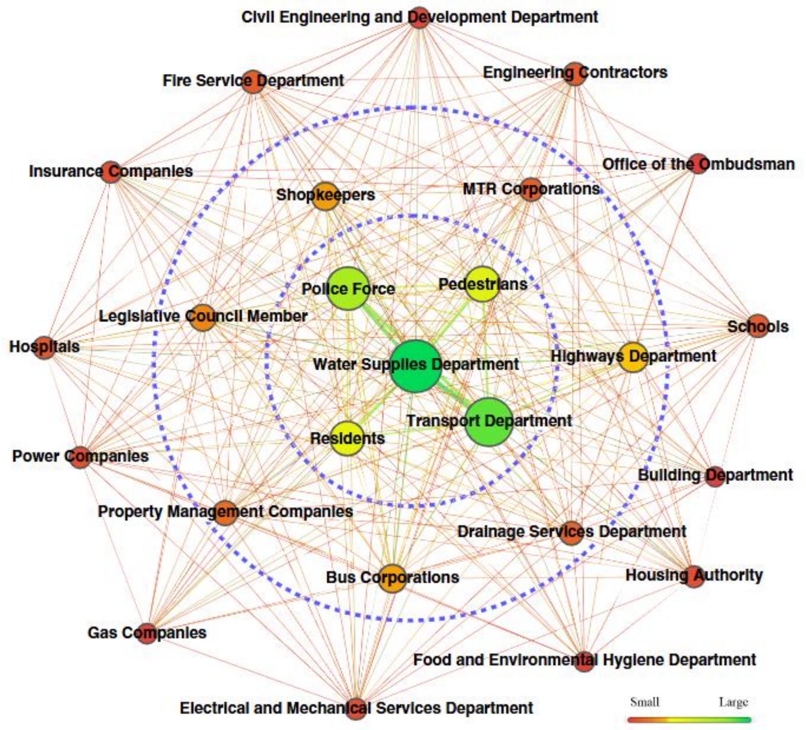
Data-driven frameworks leverage ***vast amounts of accessible data****, such as news and social media, to analyze resilience and manage disasters effectively*

Capable of integrating diverse data sources

Relies heavily on large amounts of data, which may be unavailable or inconsistent

Delineating Infrastructure Failure Interdependencies and Associated Stakeholders through News Mining: The Case of Hong Kong's Water Pipe Bursts

Shenghua Zhou, S.M.ASCE[1]; S. Thomas Ng, Ph.D.[2]; Yifan Yang[3]; and J. Frank Xu, Ph.D.[4]



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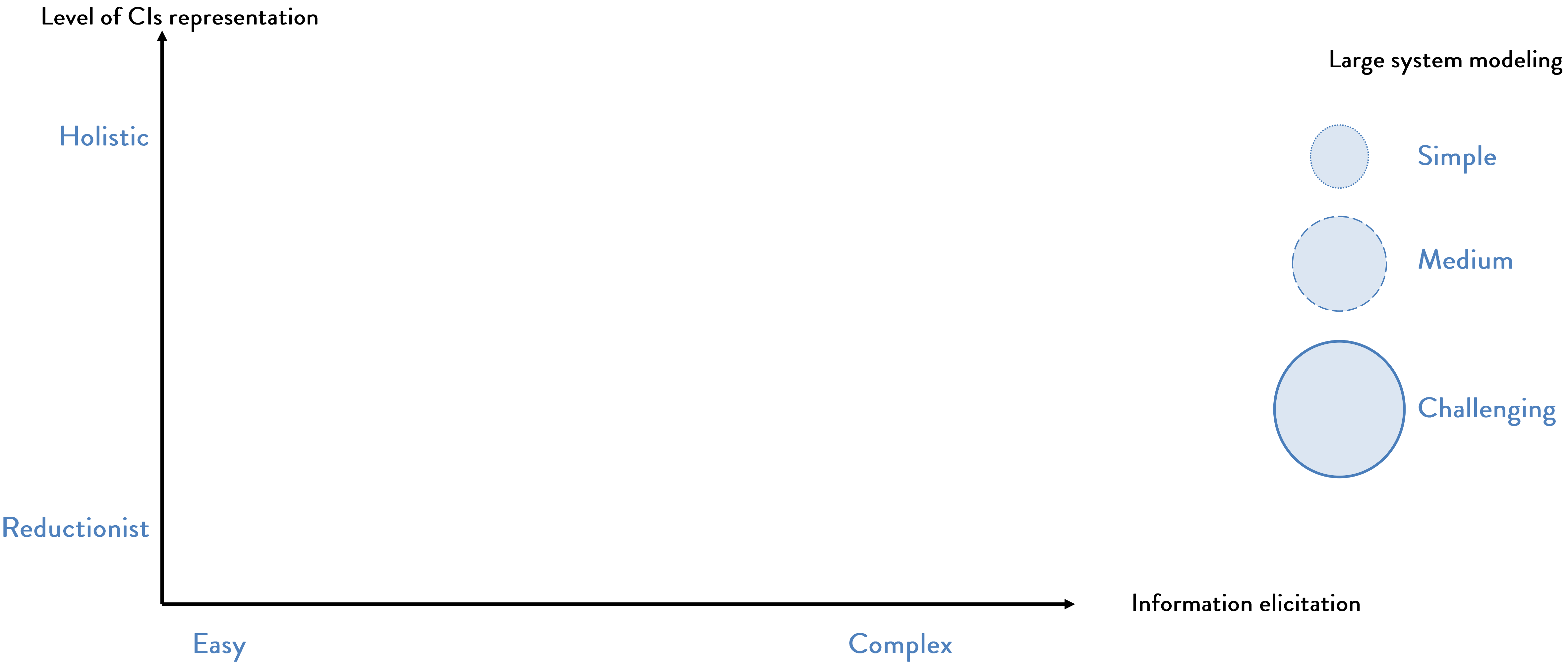
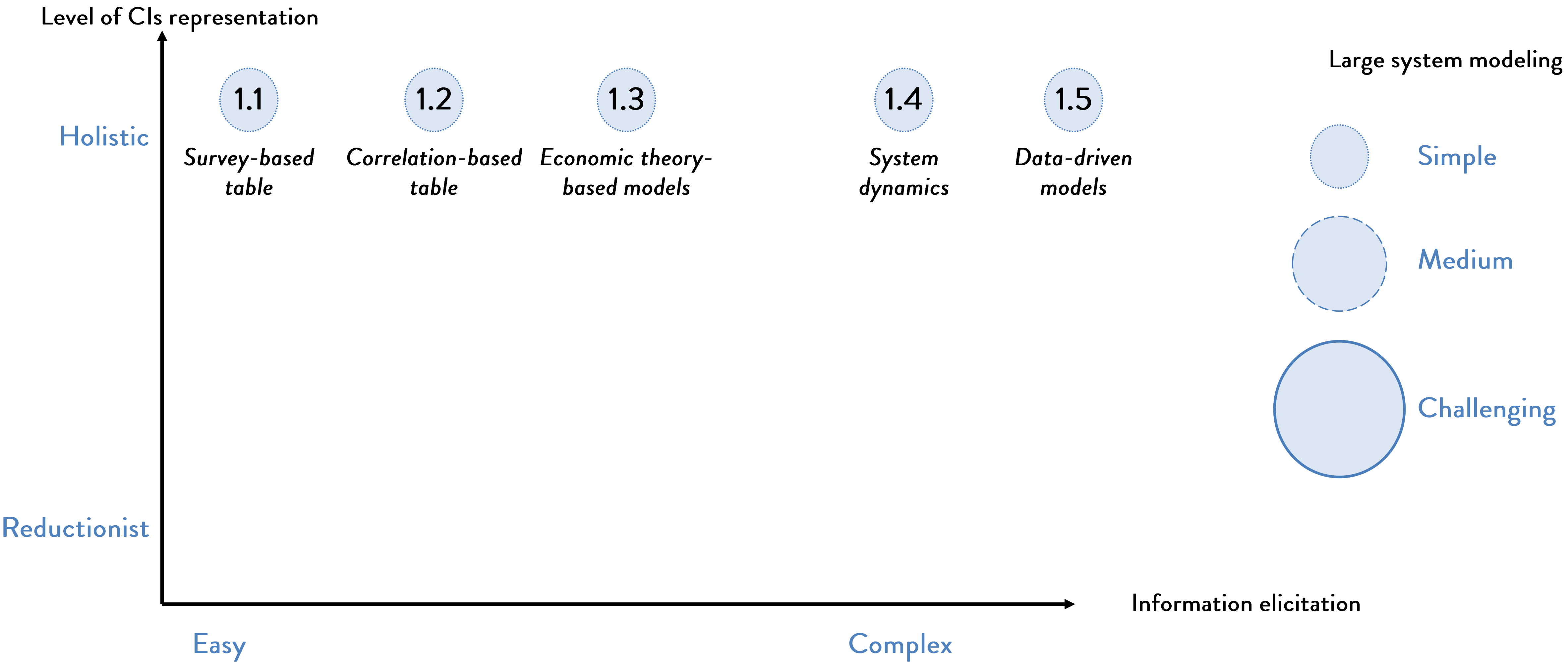
1. Interdependencies between Critical Infrastructures

1.2 Approaches Available to Model Interdependencies



1. Interdependencies between Critical Infrastructures

1.2 Approaches Available to Model Interdependencies



Vulnerability of Smart Grids with Variable Generation and Consumption: a System of Systems Perspective

Enrico Zio, *Senior Member, IEEE*, and Giovanni Sansavini

[7]

2. Reductionist Approaches

2.1 Graph theory-based models

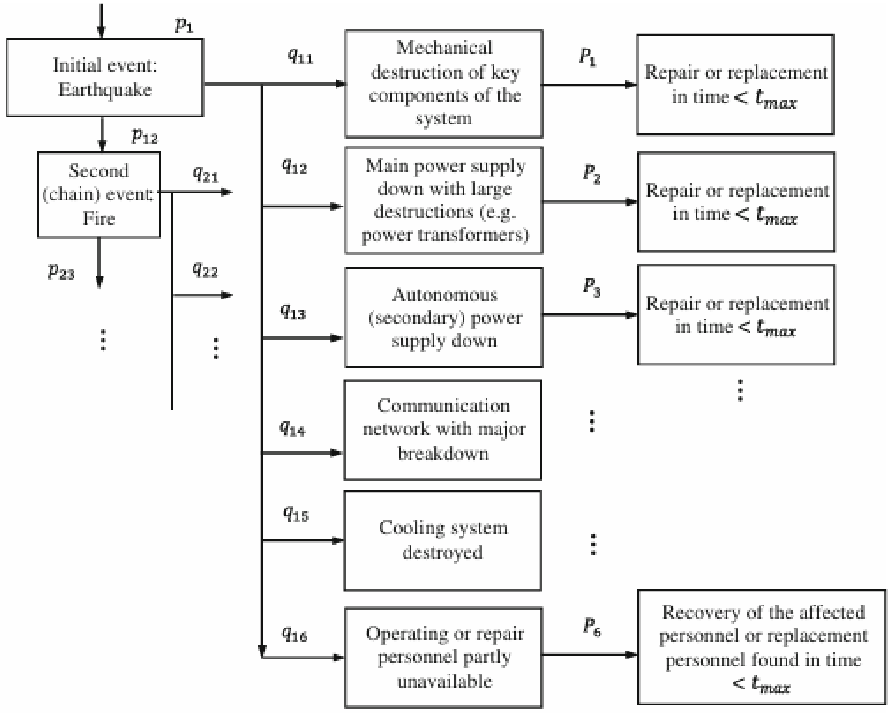
*These models use **matrices**, such as joint adjacency and probability matrices, to map interdependencies within networked systems*

Local interactions of the CI are considered

Requires extensive knowledge of network topology and node/link characteristics

Defining resilience using probabilistic event trees

Horia-Nicolai L. Teodorescu[1,2]



[8]

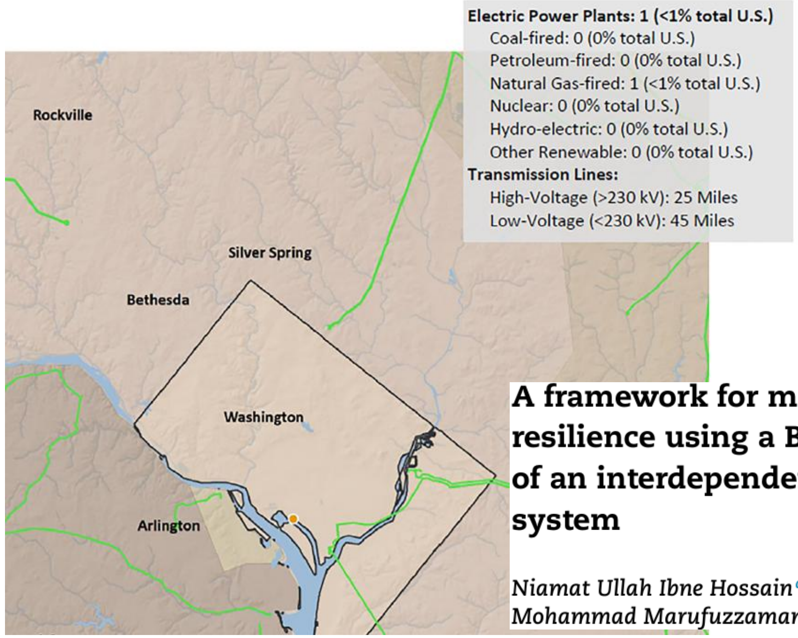
2. Reductionist Approaches

2.2 Discrete event simulation

This approach models intricate dependencies within CIs as a ***sequence of distinct events****, using sequential, conditional logic and causal relationships to assess failure probabilities under specific conditions*

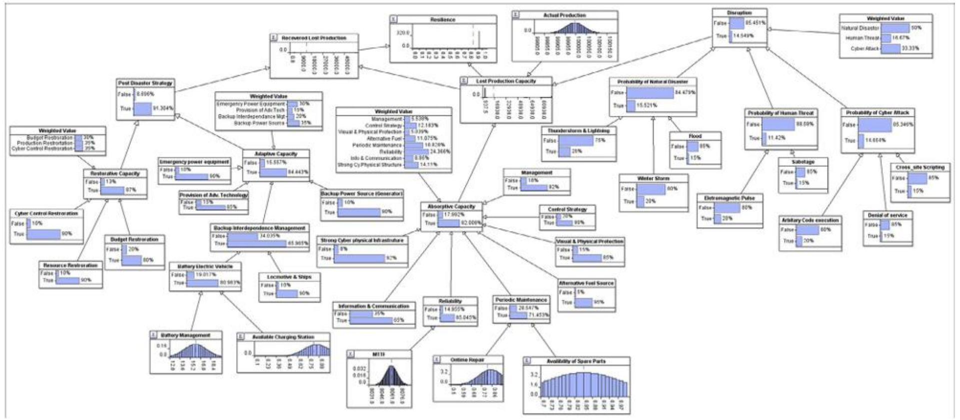
Provides clear visualization of causal relationships and event progressions

Can be computationally intensive



A framework for modeling and assessing system resilience using a Bayesian network: A case study of an interdependent electrical infrastructure system

Niamat Ullah Ibne Hossain[a], Raed Jaradat[a,], Seyedmohsen Hosseini[b], Mohammad Marufuzzaman[a], Randy K. Buchanan[c]*



[9]

2. Reductionist Approaches

2.3 Bayesian networks

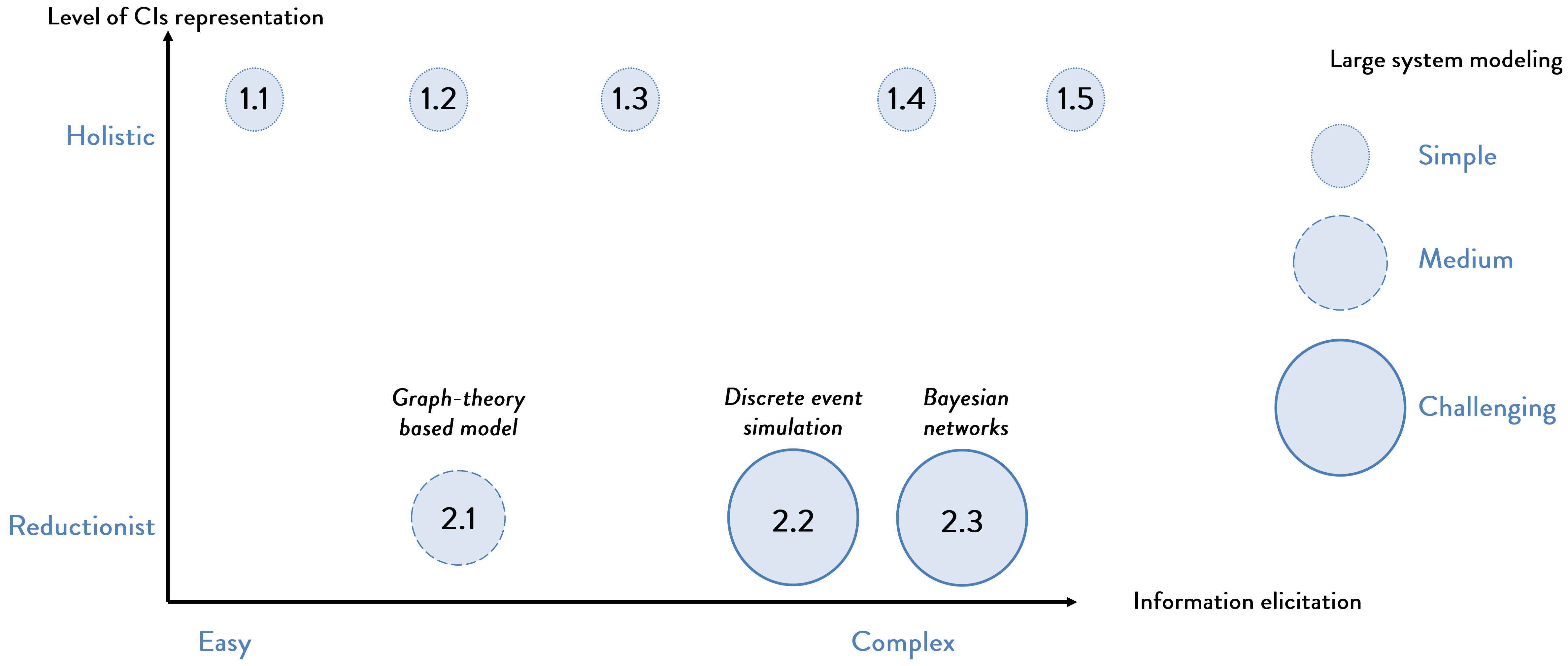
This approach models conditional dependencies using ***probabilistic graphs*** *and* ***Bayesian inference****, making it effective for assessing causation and interdependency modeling*

Effectively models and assesses causal relationships within interdependencies

Becomes increasingly computationally complex as nodes are added

1. Interdependencies between Critical Infrastructures

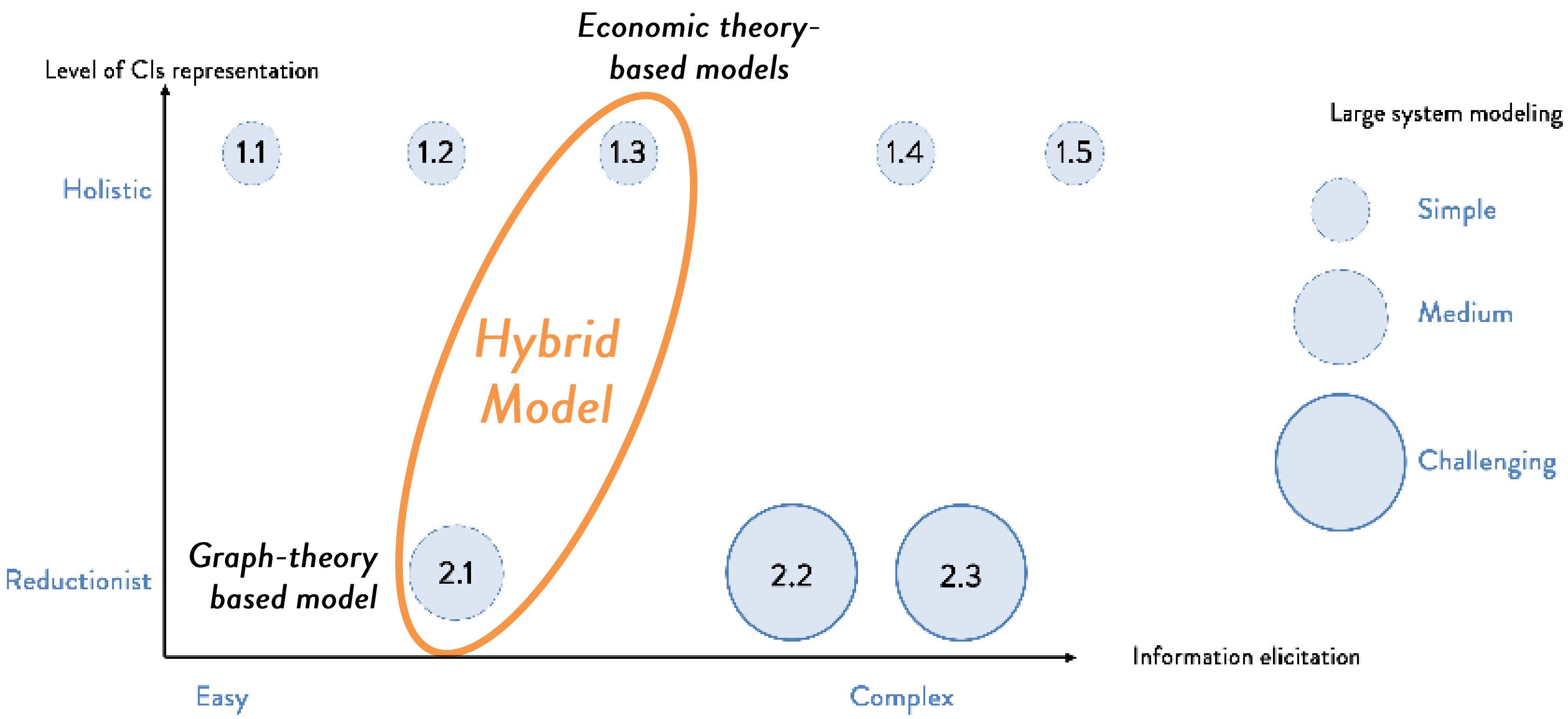
1.2 Approaches Available to Model Interdependencies



1.2 Approaches Available to Model Interdependencies

A *hybrid approach* is needed to support planners and operators, *combining scalability for strategic planning* with *detailed insights into individual CIs*

Our model combines *graph-based* and *economic approaches* to capture physical interdependencies and quantify cascading effects for resilience planning



valenclavijomesa.shinyapps.io/InterdependencyModeling/

1.2 Approaches Available to Model Interdependencies - References

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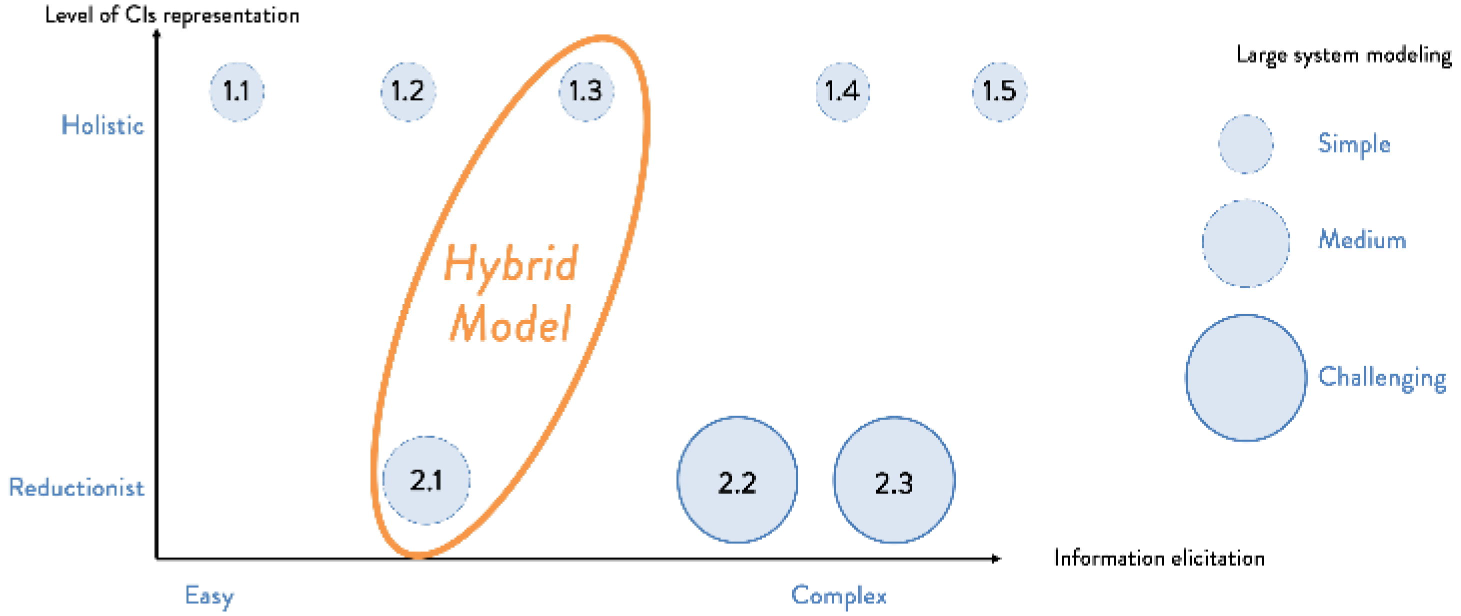
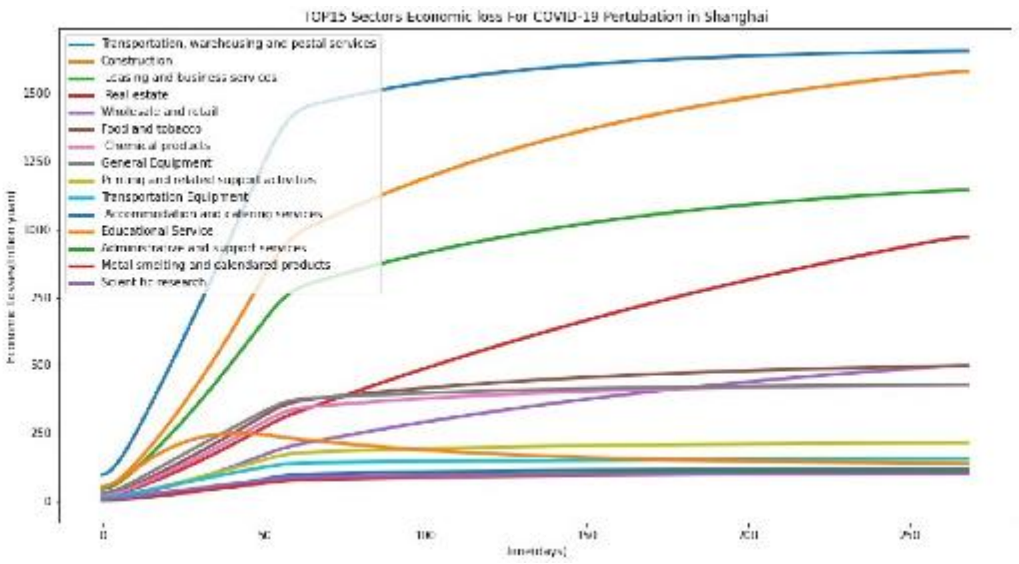
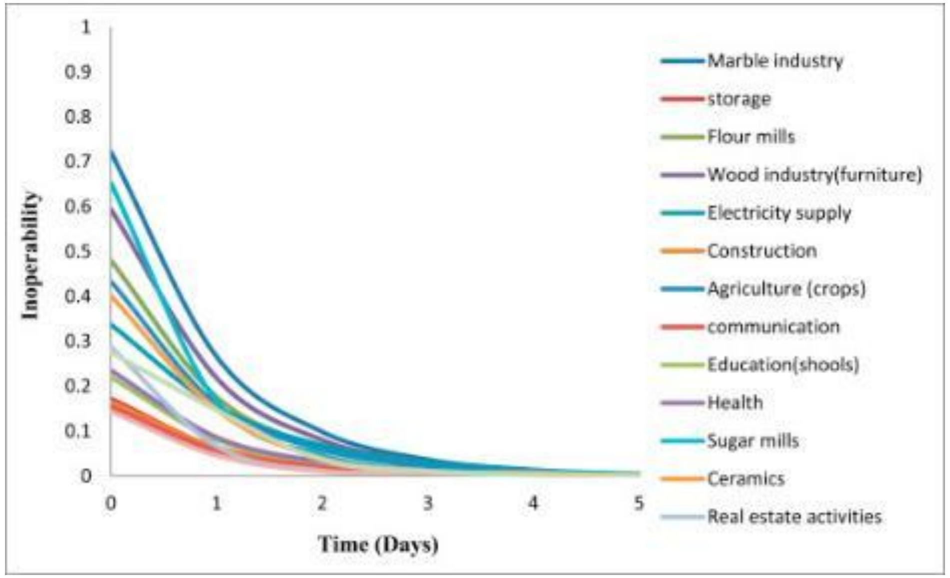
2. Hybrid Approach to Model Interdependencies



2.1 Economic Theory-based Model: DIIM

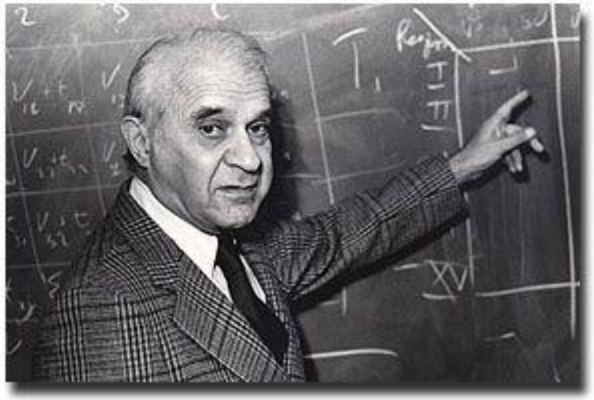




[1]

The Leontief Input-Output Analysis was developed by economist Wassily Leontief; this method analyzes how economic sectors depend on one another.

It is based on a matrix model that describes how the output from one industry becomes input for others.



He was awarded the Nobel Prize in 1973 for his work

Matrix of ***technical coefficients***, a_{ij} represents how much from industry j is needed to produce 1 unit in industry i

$$\overline{x} = \overline{\overline{A}}\,\overline{x} + \overline{c}$$

Final demand vector, i.e., c_i is the final demand for industry i

Total production output vector, i.e., x_i is the total production output for industry i

All terms are expressed in units of output, and the model assumes linear production relationships

[1]

$$\bar{\boldsymbol{x}} = \bar{\bar{\boldsymbol{A}}}\bar{\boldsymbol{x}} + \bar{\boldsymbol{c}} \ \rightarrow \left(\bar{\bar{\boldsymbol{I}}} - \bar{\bar{\boldsymbol{A}}}\right)\bar{\boldsymbol{x}} = \bar{\boldsymbol{c}} \ \rightarrow \bar{\boldsymbol{x}} = \left(\bar{\bar{\boldsymbol{I}}} - \bar{\bar{\boldsymbol{A}}}\right)^{-1}\bar{\boldsymbol{c}}$$

We solve this equation to find how much total production is needed in each industry to meet final demand, considering the interdependencies between industries

Imagine we have 3 industries: Food (F), Energy (E) and Transport (T). The interaction between them can be represented by the following matrix:

$$\bar{\bar{A}} = \begin{bmatrix} 0.1 & 0.2 & 0.1 \\ 0.3 & 0.1 & 0.2 \\ 0.2 & 0.1 & 0.1 \end{bmatrix}$$

If the final demand is $\bar{c} = \begin{bmatrix} 100 \\ 50 \\ 80 \end{bmatrix}$

Can you determine the total production vector $\bar{\boldsymbol{x}}$?

[1]

$$\bar{\boldsymbol{x}} = \bar{\bar{\boldsymbol{A}}}\bar{\boldsymbol{x}} + \bar{\boldsymbol{c}} \rightarrow (\bar{\bar{\boldsymbol{I}}} - \bar{\bar{\boldsymbol{A}}})\bar{\boldsymbol{x}} = \bar{\boldsymbol{c}} \rightarrow \bar{\boldsymbol{x}} = (\bar{\bar{\boldsymbol{I}}} - \bar{\bar{\boldsymbol{A}}})^{-1}\bar{\boldsymbol{c}}$$

$$\bar{\bar{A}} = \begin{bmatrix} 0.10 & 0.20 & 0.10 \\ 0.30 & 0.10 & 0.20 \\ 0.20 & 0.10 & 0.10 \end{bmatrix} \quad \bar{c} = \begin{bmatrix} 100 \\ 50 \\ 80 \end{bmatrix} \quad \bar{\bar{I}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$(\bar{\bar{\boldsymbol{I}}} - \bar{\bar{\boldsymbol{A}}}) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} - \begin{bmatrix} 0.10 & 0.20 & 0.10 \\ 0.30 & 0.10 & 0.20 \\ 0.20 & 0.10 & 0.10 \end{bmatrix} = \begin{bmatrix} 0.90 & -0.20 & -0.10 \\ -0.30 & 0.90 & -0.20 \\ -0.20 & -0.10 & 0.90 \end{bmatrix}$$

$$(\bar{\bar{\boldsymbol{I}}} - \bar{\bar{\boldsymbol{A}}})^{-1} = \begin{bmatrix} 0.90 & -0.20 & -0.10 \\ -0.30 & 0.90 & -0.20 \\ -0.20 & -0.10 & 0.90 \end{bmatrix}^{-1} = \begin{bmatrix} 1.26 & 0.30 & 0.21 \\ 0.49 & 1.26 & 0.33 \\ 0.33 & 0.21 & 1.19 \end{bmatrix}$$

$$\begin{bmatrix} 1.26 & 0.30 & 0.21 \\ 0.49 & 1.26 & 0.33 \\ 0.33 & 0.21 & 1.19 \end{bmatrix} \begin{bmatrix} 100 \\ 50 \\ 80 \end{bmatrix} = \bar{x}$$

Compute the total production

$\boldsymbol{x_F}, \boldsymbol{x_E}, \boldsymbol{x_T}$

2. Hybrid Approach to Model Interdependencies

2.1 Economic Theory-based Model: DIIM

[1]

$$\bar{\boldsymbol{x}} = \bar{\bar{\boldsymbol{A}}}\bar{\boldsymbol{x}} + \bar{\boldsymbol{c}} \rightarrow \left(\bar{\bar{\boldsymbol{I}}} - \bar{\bar{\boldsymbol{A}}}\right)\bar{\boldsymbol{x}} = \bar{\boldsymbol{c}} \rightarrow \bar{\boldsymbol{x}} = \left(\bar{\bar{\boldsymbol{I}}} - \bar{\bar{\boldsymbol{A}}}\right)^{-1}\bar{\boldsymbol{c}}$$

$$\bar{\bar{A}} = \begin{bmatrix} 0.10 & 0.20 & 0.10 \\ 0.30 & 0.10 & 0.20 \\ 0.20 & 0.10 & 0.10 \end{bmatrix} \quad \bar{c} = \begin{bmatrix} 100 \\ 50 \\ 80 \end{bmatrix} \quad \bar{\bar{I}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\left(\bar{\bar{\boldsymbol{I}}} - \bar{\bar{\boldsymbol{A}}}\right) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} - \begin{bmatrix} 0.10 & 0.20 & 0.10 \\ 0.30 & 0.10 & 0.20 \\ 0.20 & 0.10 & 0.10 \end{bmatrix} = \begin{bmatrix} 0.90 & -0.20 & -0.10 \\ -0.30 & 0.90 & -0.20 \\ -0.20 & -0.10 & 0.90 \end{bmatrix}$$

$$\left(\bar{\bar{\boldsymbol{I}}} - \bar{\bar{\boldsymbol{A}}}\right)^{-1} = \begin{bmatrix} 0.90 & -0.20 & -0.10 \\ -0.30 & 0.90 & -0.20 \\ -0.20 & -0.10 & 0.90 \end{bmatrix}^{-1} = \begin{bmatrix} 1.26 & 0.30 & 0.21 \\ 0.49 & 1.26 & 0.33 \\ 0.33 & 0.21 & 1.19 \end{bmatrix}$$

$$\begin{bmatrix} 1.26 & 0.30 & 0.21 \\ 0.49 & 1.26 & 0.33 \\ 0.33 & 0.21 & 1.19 \end{bmatrix}\begin{bmatrix} 100 \\ 50 \\ 80 \end{bmatrix} = \bar{x} = \begin{bmatrix} 157.8 \\ 138.4 \\ 138.7 \end{bmatrix}$$

The Food industry must produce **157.8 units**, the Energy industry must produce **138.4 units**, and the Transport industry must produce **138.7 units**,

To meet the final demand of **100**, **50**, and **80** respectively, considering interdependencies

How to obtain the Leontief coefficient matrix?

	Cotton	...
F	100	
G	120	
H	90	

	S	T	W
Cotton	170	85	45
Polyester	30	95	165
⋮			

	Cotton	...
F	100	
G	120	
H	90	
	310	

	S	T	W
Cotton	170	85	45
Polyester	30	95	165
⋮			
	250	320	510

$$a_{FS} = \frac{100}{310} \times \frac{170}{250} = 0.22$$

$$a_{FT} = \frac{100}{310} \times \frac{85}{320} = 0.09$$

$$a_{FW} = \frac{100}{310} \times \frac{45}{510} = 0.03$$

What are the values of a_{GT} and a_{HW}?

$$a_{GT} = \frac{120}{310} \times \frac{85}{320} = 0.10$$

$$a_{HW} = \frac{90}{310} \times \frac{45}{510} = 0.03$$

[2]

2001

$$\bar{x} = \bar{\bar{A}}\bar{x} + \bar{c}$$

LEONTIEF-BASED MODEL OF RISK IN COMPLEX INTERCONNECTED INFRASTRUCTURES

By Yacov Y. Haimes[1] and Pu Jiang[2]

$$\bar{q} = \bar{\bar{A}}\bar{q} + \bar{c}$$

Inoperability vector of critical infrastructure, i.e., q_i is the inability (expressed as a percentage) of the i-th CI to operate correctly

Perturbation vector, i.e., c_i is the initial perturbation affecting the i-th CI due to external factors

Matrix of ***interdependency coefficients***, a_{ij} represents the fraction of inoperability that the j-th CI contributes to the i-th CI due to their interdependencies

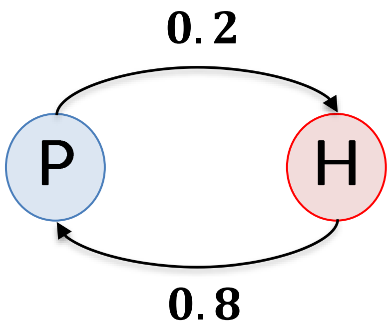
Inoperability Input-output Model

[2]

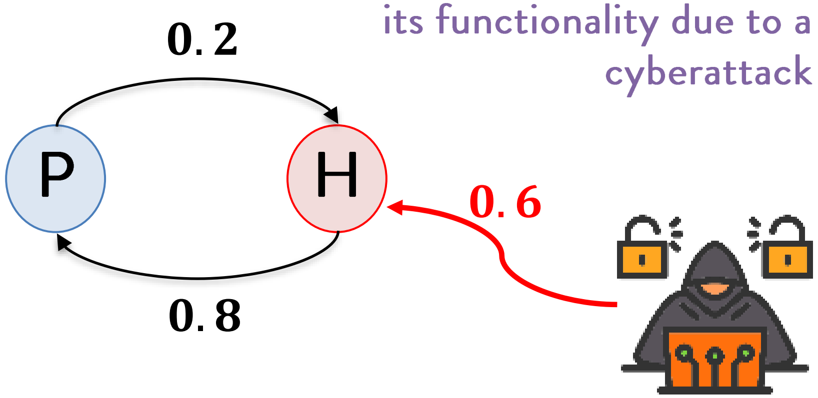
To show how to apply the Inoperability Input-output Model (IIM), we will solve the following example.

Imagine we have ***two infrastructures***.
The inoperability is represented by q_P and q_H

Suppose a failure in infrastructure H causes infrastructure P to become 80% inoperable, and a failure in infrastructure P causes infrastructure H to become 20% inoperable



Now suppose that infrastructure H loses 60% of its functionality due to a cyberattack



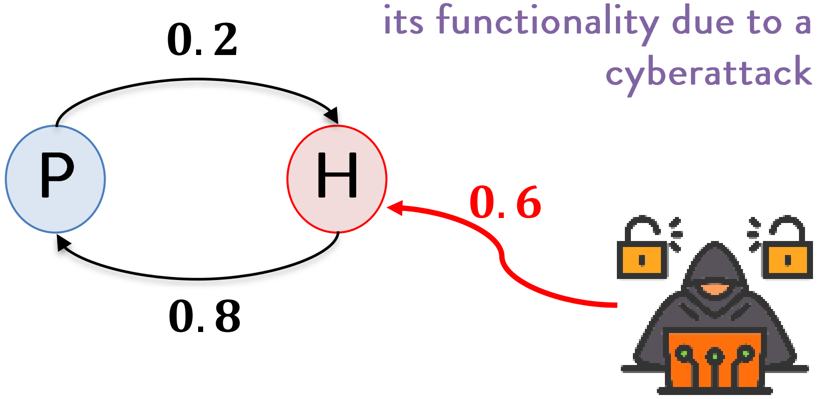
Then $\bar{\bar{A}} = \begin{bmatrix} 0 & 0.8 \\ 0.2 & 0 \end{bmatrix}$

Estimate the inoperability of both infrastructures

[2]

$$\bar{\boldsymbol{q}} = \bar{\bar{\boldsymbol{A}}}\bar{\boldsymbol{q}} + \bar{\boldsymbol{c}} \qquad \bar{\bar{A}} = \begin{bmatrix} 0 & 0.8 \\ 0.2 & 0 \end{bmatrix} \qquad \bar{c} = \begin{bmatrix} 0 \\ 0.6 \end{bmatrix}$$

Now suppose that infrastructure H loses 60% of its functionality due to a cyberattack



$$\begin{bmatrix} q_P \\ q_H \end{bmatrix} = \begin{bmatrix} 0 & 0.8 \\ 0.2 & 0 \end{bmatrix} \begin{bmatrix} q_P \\ q_H \end{bmatrix} + \begin{bmatrix} 0 \\ 0.6 \end{bmatrix}$$

$$\begin{bmatrix} q_P \\ q_H \end{bmatrix} = \begin{bmatrix} 0.8 q_H \\ 0.2 q_P + 0.6 \end{bmatrix}$$

Estimate the inoperability of both infrastructures

Note that *inoperability of infrastructure P* is $\mathbf{0.571}$, even though *it was not directly attacked*.

$$\begin{bmatrix} q_P \\ q_H \end{bmatrix} = \begin{bmatrix} 0.571 \\ 0.714 \end{bmatrix}$$

This effect is purely due to the ***interdependency*** *between the two infrastructures.*

The *inoperability of infrastructure H* also *increases* by $\mathbf{0.114}$ due to its interdependency with infrastructure P

[2]

Given the following description of interactions between four infrastructures, identify which interdependency matrix correctly represents the scenario

If the ***power plant*** fails completely, then the ***transportation system*** can perform only 60% of its functionality, whereas both the ***hospital*** and the ***grocery store*** cannot operate at all.

If the ***transportation system*** fails completely, meaning workers and deliveries cannot reach their destinations, the ***power plant*** and the ***grocery store*** can each operate at only 10%, and the ***hospital*** at 20%.

On the other hand, the inoperability of the ***hospital*** or ***grocery store*** does not affect the operation of the ***power plant*** or the ***transportation system***, nor do they significantly affect each other.

$$\bar{\bar{A}} = \begin{bmatrix} 0 & 0.9 & 0 & 0 \\ 0.4 & 0 & 0 & 0 \\ 1 & 0.8 & 0 & 0 \\ 1 & 0.9 & 0 & 0 \end{bmatrix}$$

$$\bar{\bar{A}} = \begin{bmatrix} 0 & 0.9 & 0 & 0 \\ 0.6 & 0 & 0 & 0 \\ 1 & 0.8 & 0 & 0 \\ 1 & 0.9 & 0 & 0 \end{bmatrix}$$

$$\bar{\bar{A}} = \begin{bmatrix} 0 & 0.1 & 0 & 0 \\ 0.6 & 0 & 0 & 0 \\ 1 & 0.2 & 0 & 0 \\ 1 & 0.1 & 0 & 0 \end{bmatrix}$$

[3]

Using the interdependency matrix, it is possible to estimate two indices:

Dependency index

$$\boldsymbol{\delta_i = \sum_{j=1}^{n} a_{ij}}$$

measures how much infrastructure i depends on other infrastructures

- *A **higher value** means infrastructure i becomes **highly inoperable when others fail**. It is less robust.*
- *A **lower value** means it can **maintain functionality** even when others are disrupted.*

Influence index

$$\boldsymbol{\theta_j = \sum_{i=1}^{n} a_{ij}}$$

measures how much infrastructure j influences the inoperability of others

- *A **higher value** means failures in infrastructure j can cause **widespread disruptions**.*
- *A **lower value** means its failure has **limited impact** on other infrastructures.*

Given the following interdependency matrix (ordered as: Power plant, Transportation system, Hospital, Grocery store), estimate the *dependency* and *influence* indices for each infrastructure.

Which infrastructure is the least robust, and which one has the greatest influence on the others?

$$\bar{\bar{A}} = \begin{bmatrix} 0 & 0.9 & 0 & 0 \\ 0.4 & 0 & 0 & 0 \\ 1 & 0.8 & 0 & 0 \\ 1 & 0.9 & 0 & 0 \end{bmatrix}$$

Infrastructure	Dependency index (δ_i)	Influence index (θ_j)
Power plant	0.9	2.4
Transportation system	0.4	2.6
Hospital	1.8	0
Grocery store	1.9	0

Least robust: Grocery store

Greatest influence: Transportation system

[4]

2005

$$\bar{q} = \bar{\bar{A}}\bar{q} + \bar{c}$$

Inoperability Input-Output Model for Interdependent Infrastructure Sectors. I: Theory and Methodology

Yacov Y. Haimes, F.ASCE[1]; Barry M. Horowitz[2]; James H. Lambert, M.ASCE[3]; Joost R. Santos[4]; Chenyang Lian[5]; and Kenneth G. Crowther[6]

$$\bar{q}(t+1) - \bar{q}(t) = \bar{\bar{K}}\left[\bar{\bar{A}}\bar{q}(t) + \bar{c}(t) - \bar{q}(t)\right]$$

Matrix of ***resilience coefficients***,

k_{ii} measures the recovery rate of the i-th CI, i.e., how quickly the i-th CI can recovery from inoperability.
Larger coefficients correspond to faster infrastructure recovery

Dynamic Inoperability Input-output Model

[5]

How to obtain the resilience coefficients?

$$\boldsymbol{k_{ii} = \frac{1}{T_i(1 - a_{ii})} ln\left(\frac{q_i(0)}{q_i(T_i)}\right)}$$

$q_i(0)$ the initial inoperability of the i-th CI;

$q_i(T_i)$ the inoperability that decision-makers of the i-th CI would like to achieve;

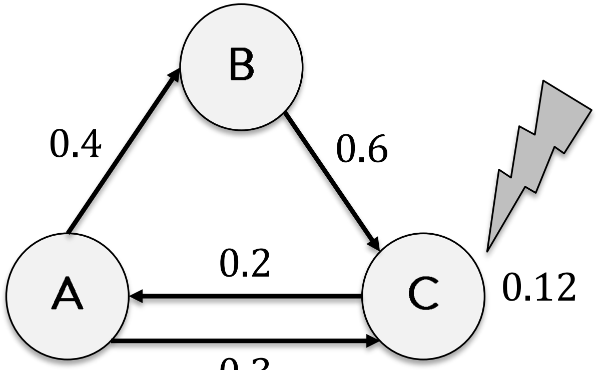
T_i the required time to reach $q_i(T_i)$;

If $\boldsymbol{T_i}$ is estimated by experts as the time required for the i-th CI to reduce its inoperability from 100% to a negligible value such as 1%, then:

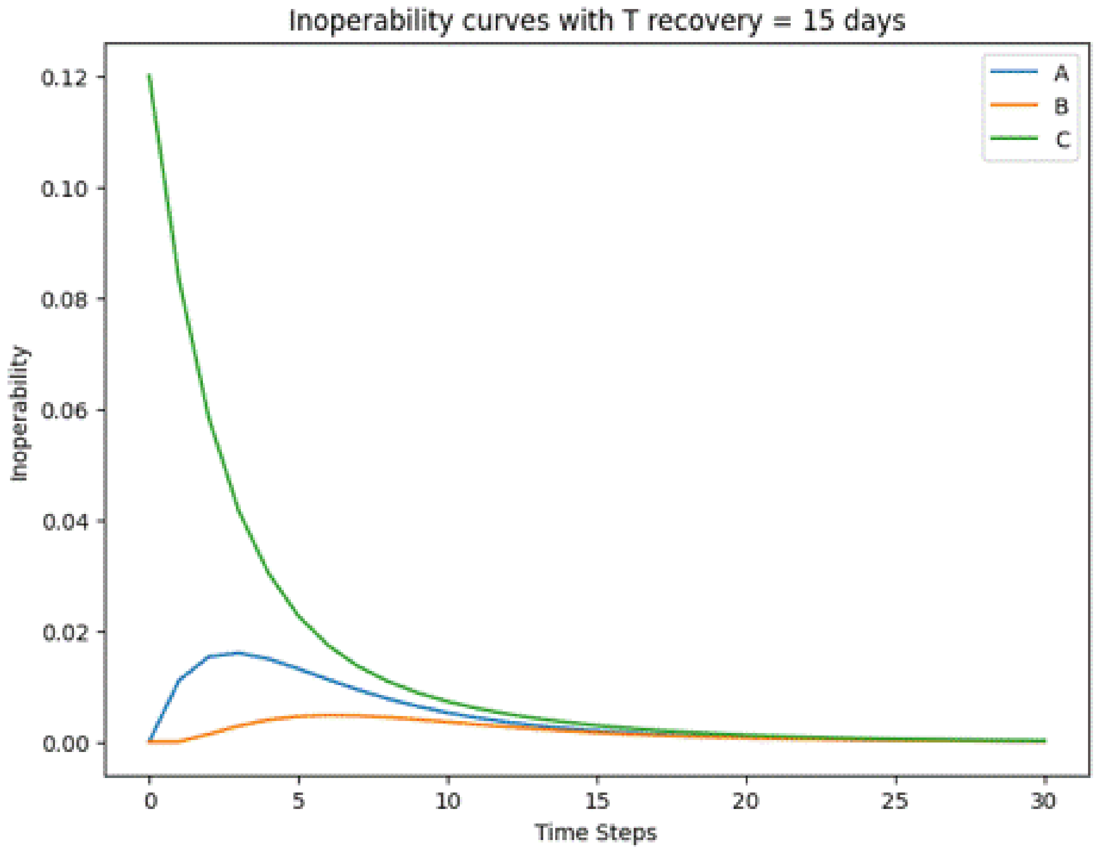
$$\boldsymbol{ln\left(\frac{q_i(0)}{q_i(T_i)}\right) = ln\left(\frac{1}{0.01}\right) = ln(100)}$$

2. Hybrid Approach to Model Interdependencies

2.1 Economic Theory-based Model: DIIM



$$\bar{\bar{A}} = \begin{bmatrix} 0 & 0 & 0.3 \\ 0.4 & 0 & 0 \\ 0.2 & 0.6 & 0 \end{bmatrix}$$



$$\bar{\bar{K}} = \begin{bmatrix} 0.31 & 0 & 0 \\ 0 & 0.31 & 0 \\ 0 & 0 & 0.31 \end{bmatrix}$$

[6] Static and dynamic metrics of economic resilience for interdependent infrastructure and industry sectors

Raghav Pant [a], Kash Barker [b,*], Christopher W. Zobel [c]

[a] Environmental Change Institute, Centre for the Environment, University of Oxford, Oxford, UK
[b] School of Industrial and Systems Engineering, University of Oklahoma, Norman, OK 73019, USA
[c] Department of Business Information Technology, Virginia Polytechnic Institute and State University, VA, USA

Sample **A** matrix from the BEA 2011 input–output accounts.

IOCode	Commodities/industries Name	11 Agriculture	22 Utilities	23 Construction	48TW Transportation
11	Agriculture	0.1949842	0.0000011	0.0010711	0.0000444
21	Mining	0.0027765	0.1331650	0.0083818	0.0014131
22	Utilities	0.0154424	0.0002903	0.0032619	0.0028235
23	Construction	0.0044906	0.0107309	0.0007315	0.0075727
31G	Manufacturing	0.2005193	0.0080531	0.2442287	0.1873453
42	Wholesale trade	0.0475103	0.0010087	0.0232085	0.0135453
44RT	Retail trade	0.0018242	0.0000471	0.0359828	0.0047366
48TW	Transportation and warehousing	0.0215651	0.0341889	0.0134875	0.0862129
51	Information	0.0006798	0.0008374	0.0060602	0.0049617
FIRE	Finance, real estate	0.0782274	0.0066511	0.0300241	0.0548634
PROF	Professional services	0.0103202	0.0129371	0.0812154	0.0614684
6	Educational services	0.0021031	0.0000422	0.0000136	0.0000766
7	Arts, entertainment	0.0010167	0.0029302	0.0026978	0.0082843
81	Other services	0.0019078	0.0004941	0.0130497	0.0053673
G	Government	0.0002524	0.0001314	0.0000283	0.0105593

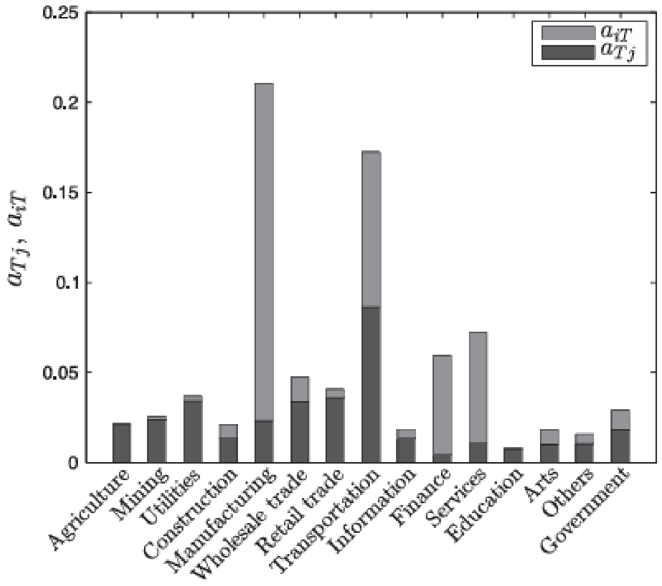
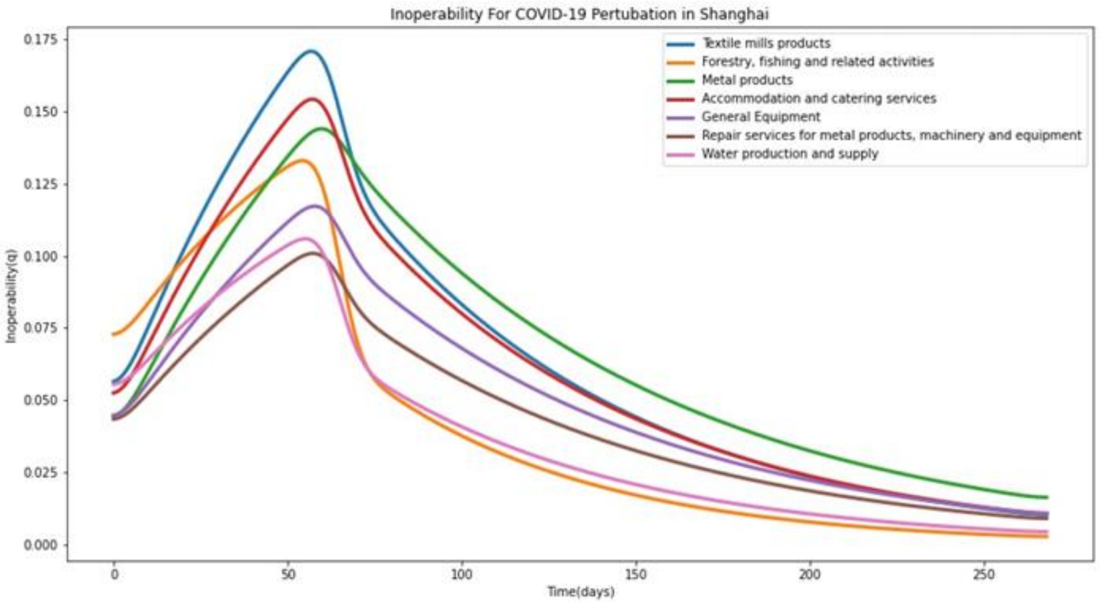


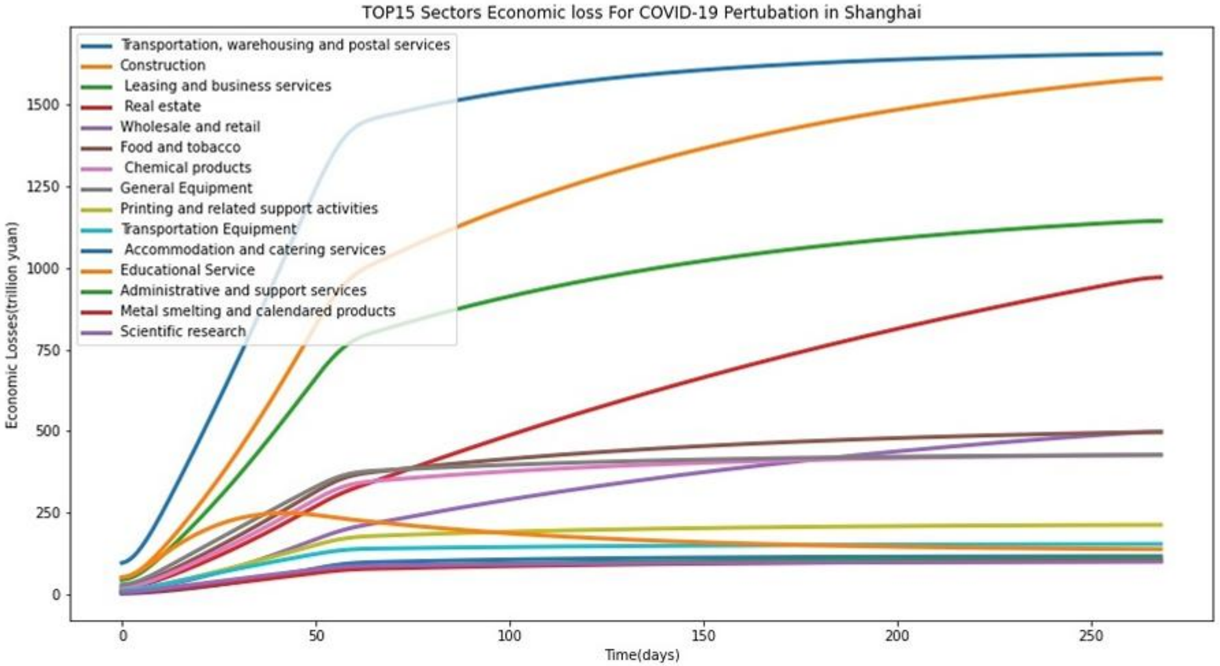
Fig. 1. Sample relationship among the Transportation sector and others.

[7] *Article*

A Demand-Side Inoperability Input–Output Model for Strategic Risk Management: Insight from the COVID-19 Outbreak in Shanghai, China

Jian Jin * and Haoran Zhou





[8] **Critical infrastructure dependency assessment using the input–output inoperability model**

Roberto Setola[a,*], *Stefano De Porcellinis*[a], *Marino Sforna*[b]

[a] *Complex Systems and Security Laboratory, University Campus BioMedico, Rome, Italy*
[b] *TERNA – Italian Transmission System Operator, Rome, Italy*

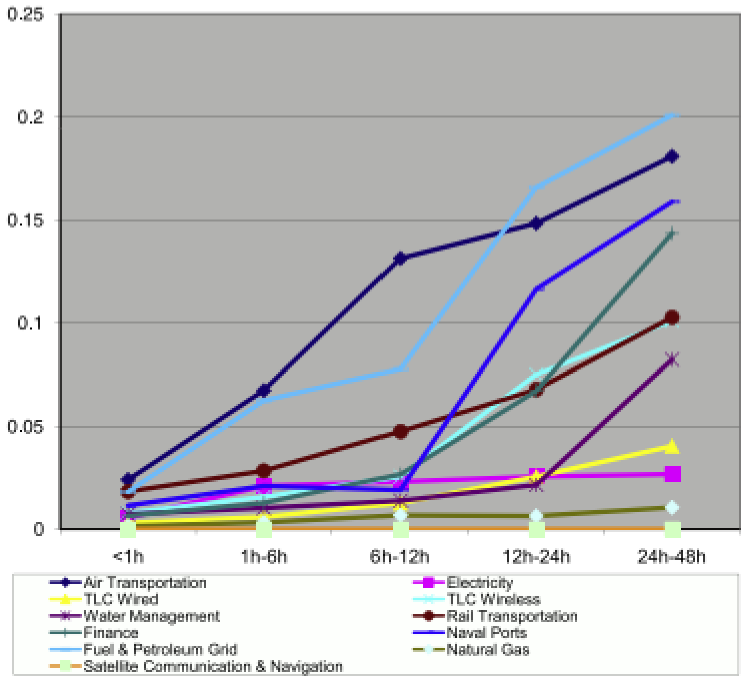


Fig. 4 – Dependency indices δ_i for various outage periods.

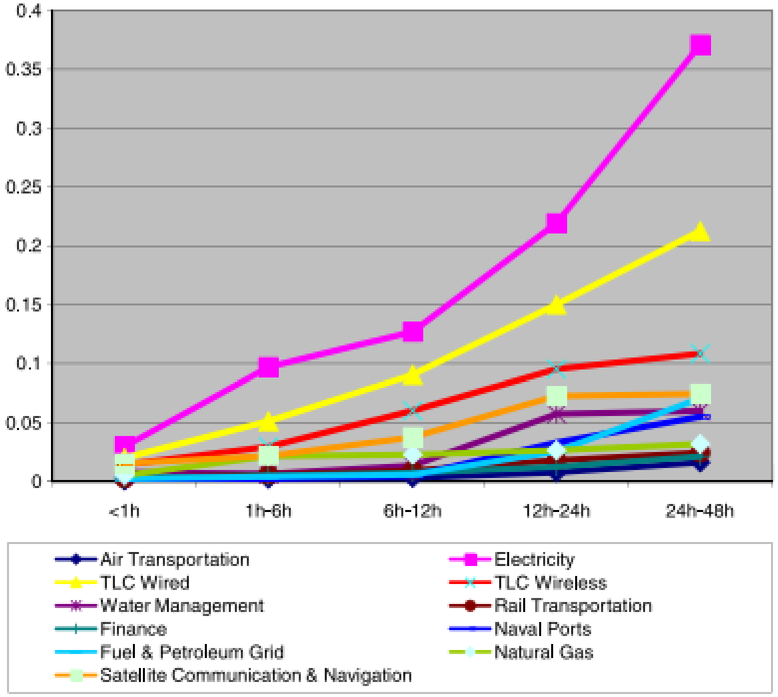


Fig. 5 – Influence gains ρ_j for various outage periods.

2. Hybrid Approach to Model Interdependencies

2.1 Economic Theory-based Model: DIIM - References

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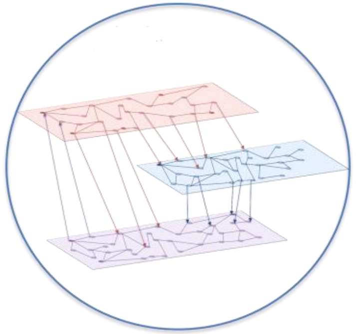
2. Hybrid Approach to Model Interdependencies

2.2 Multi-state DIIM

Interdependencies



Economic theory-based models

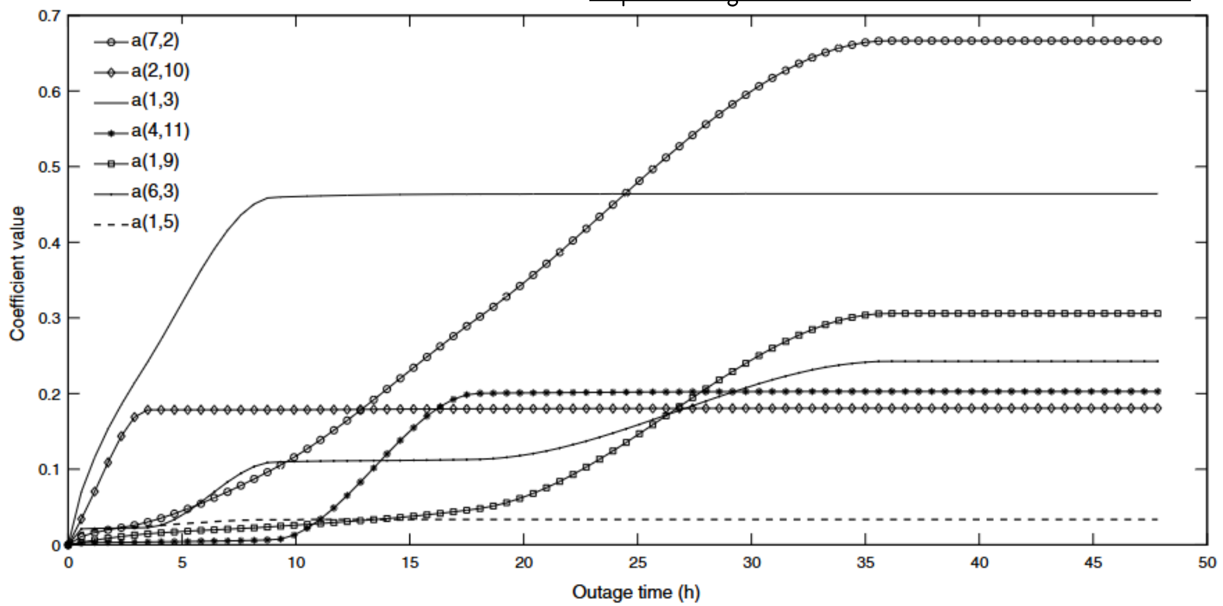
↓

Dynamic Inoperability Input-output Model (DIIM)

$$\bar{q}(t+1) = \bar{q}(t) - \bar{\bar{K}}\bar{q}(t) + \bar{\bar{K}}\bar{\bar{A}}\bar{q}(t) + \bar{\bar{K}}\bar{c}(t)$$

Can interdependencies between CIs be considered ***static***, or do they ***dynamically evolve*** with the changing operational states of the systems?

https://doi.org/10.1061/(ASCE)IS.1943-555X.0000099



Setola et al. (2012) modeled *time-varying interdependencies* by outage duration, but these also evolve with the operational states of infrastructures.

Multi-state DIIM

$$\bar{q}(t+1) = \bar{q}(t) - \bar{\bar{K}}\bar{q}(t) + \bar{\bar{K}}\bar{\bar{A}}(t)\bar{q}(t) + \bar{\bar{K}}\bar{c}(t)$$

2. Hybrid Approach to Model Interdependencies

2.2 Multi-state DIIM

Multi-state DIIM: Procedure

$$\bar{q}(t+1) = \bar{q}(t) - \bar{\bar{K}}\bar{q}(t) + \bar{\bar{K}}\bar{\bar{A}}(t)\bar{q}(t) + \bar{\bar{K}}\bar{c}(t)$$

- Represent each CI as a **networks**,
- *Define dependency pairs* $(i \rightarrow j)$ *between infrastructures,*
- *Generate* S *disruption scenarios on the source CI* (i) *and simulate cascading effects*
- *Record the inoperability* $O(X_s^i)$, $O(X_s^j)$ *for both CIs across* S

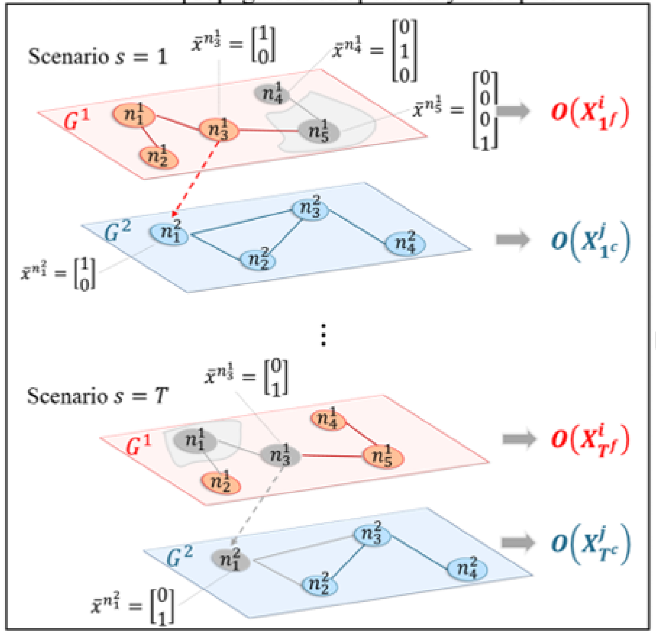
$$O(X_s^i) = 1 - \frac{D(X_s^i)}{D(X_0^i)} \qquad O(X_s^j) = 1 - \frac{D(X_s^j)}{D(X_0^j)}$$

- Discretize inoperability levels into intervals,
- *Estimate conditional probabilities* $\bar{\bar{R}}_{i\rightarrow j}$

$$\mathbb{P}\left(O\left(X_d^j\right) \in r_l^j \,\middle|\, O\left(X_z^i\right) \in r_k^i\right)$$

- Compute expected *state-dependent coefficient* $a_{i\rightarrow j}(\bar{q}_i(t))$

Generation and propagation of operability disruptions



Estimation of values in the conditional probability matrix $\bar{\bar{R}}_{1\rightarrow 2}$

$r^1 = \{[0, 0.2], (0.2, 0.6], (0.6, 0.9], (0.9, 1]\}$

$r^2 = \{[0, 0.3], (0.3, 0.8], (0.8, 1]\}$

r^1 \ r^2	[0, 0.3]	(0.3, 0.8]	(0.8, 1]
[0, 0.2]	1	0	0
(0.2, 0.6]	0.25	0.55	0.20
(0.6, 0.9]	0.15	0.45	0.40
(0.9, 1]	0	0.3	0.7

Quantification of interdependency coefficients $a_{21}[r^1]$

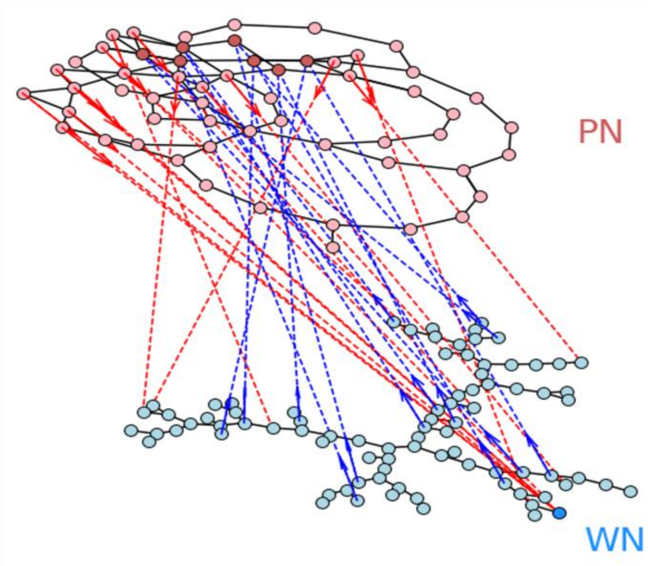
r^1	a_{21}	a_{21}
[0, 0.2]	$(0.3 \times 1) + (0.8 \times 0) + (1 \times 0)$	$a_{21} = 0.3 \;\; \forall \;\; 0 \le q_2 \le 0.2$
(0.2, 0.6]	$(0.3 \times 0.25) + (0.8 \times 0.55) + (1 \times 0.2)$	$a_{21} = 0.72 \;\; \forall \;\; 0.2 < q_2 \le 0.6$
(0.6, 0.9]	$(0.3 \times 0.15) + (0.8 \times 0.45) + (1 \times 0.4)$	$a_{21} = 0.81 \;\; \forall \;\; 0.6 < q_2 \le 0.9$
(0.9, 1]	$(0.3 \times 0) + (0.8 \times 0.3) + (1 \times 0.7)$	$a_{21} = 0.94 \;\; \forall \;\; 0.9 < q_2 \le 1$

2. Hybrid Approach to Model Interdependencies

2.2 Multi-state DIIM

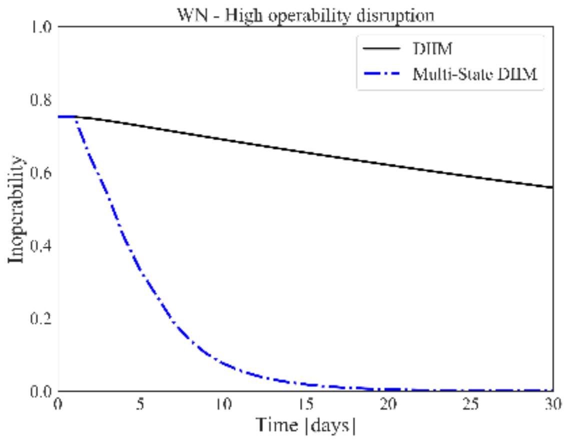
Interdependency model

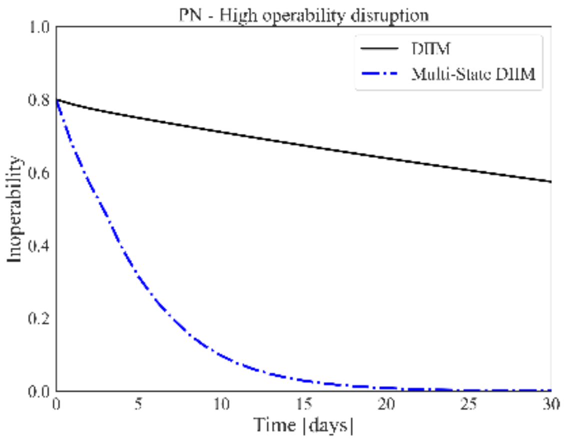
https://doi.org/10.1016/j.ress.2025.111303



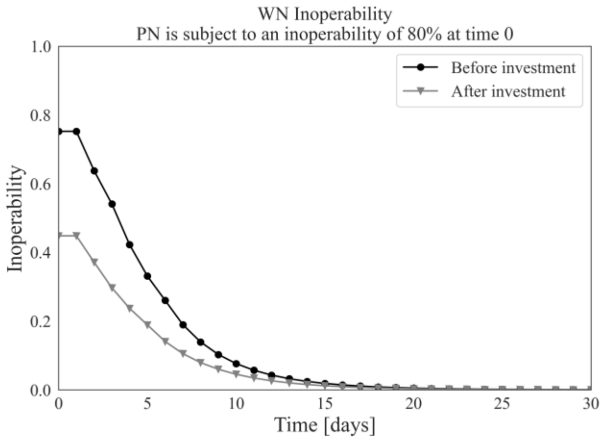
Multi-state DIIM was applied to an ***interdependent Power-Water Network***

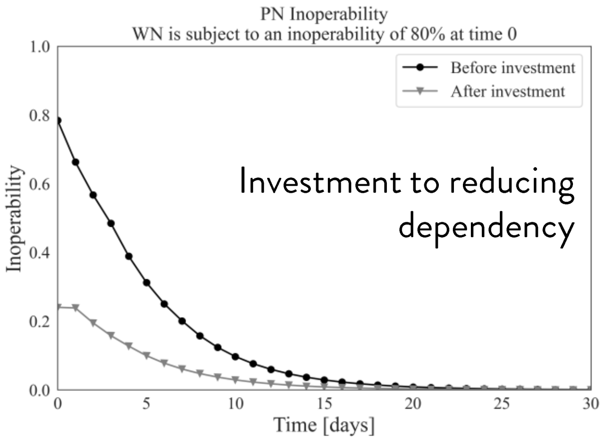
Compared to traditional DIIM, it is ***less conservative***



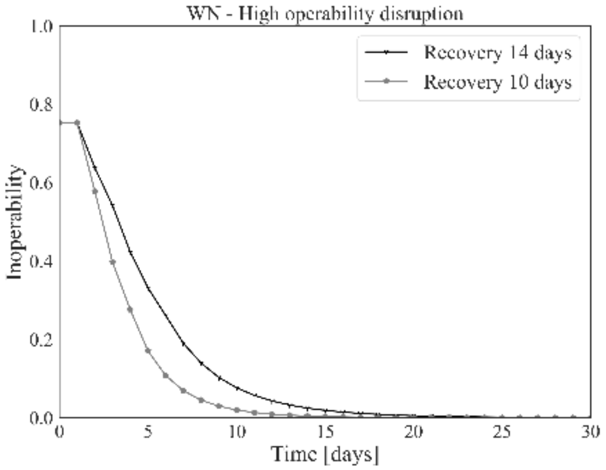


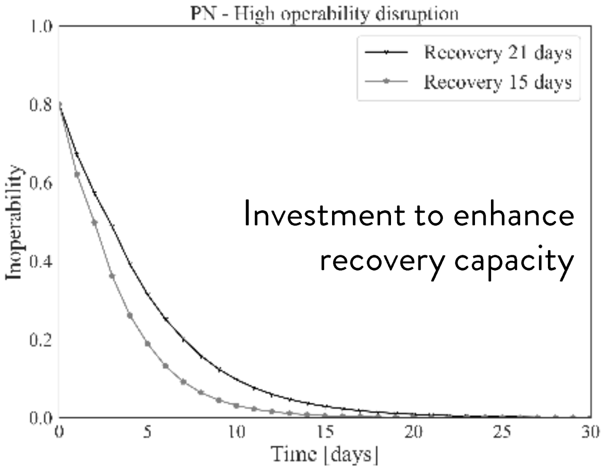
By modeling each CI as a network, it becomes possible to ***re-evaluate interdependencies*** under different strategies, such as:





Investment to reducing dependency



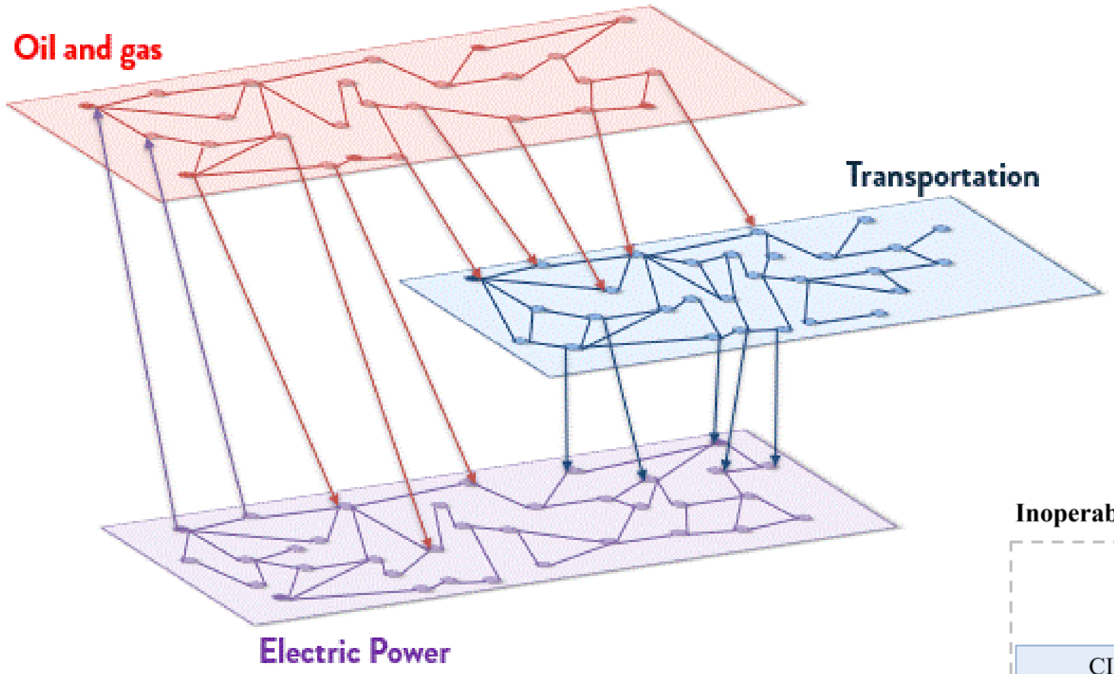


Investment to enhance recovery capacity

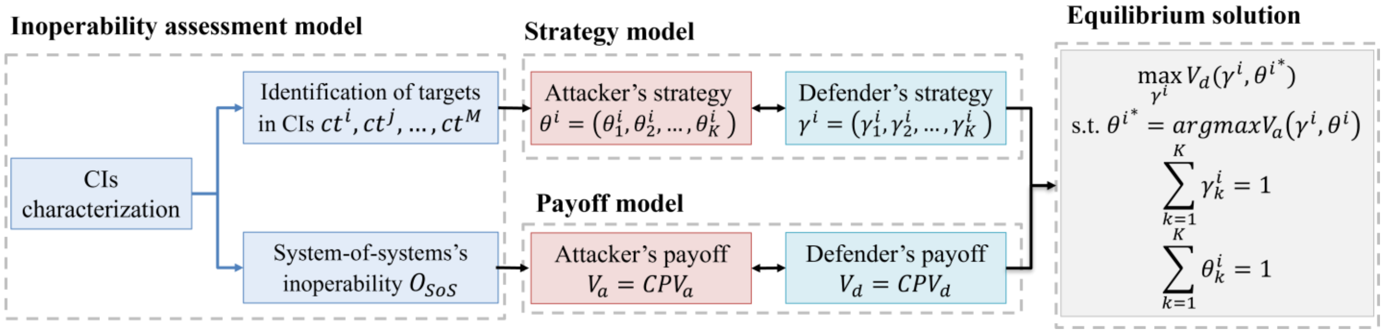
2. Hybrid Approach to Model Interdependencies

2.2 Multi-state DIIM

10.3850/978-981-94-3281-3_ESREL-SRA-E2025-P7627-cd



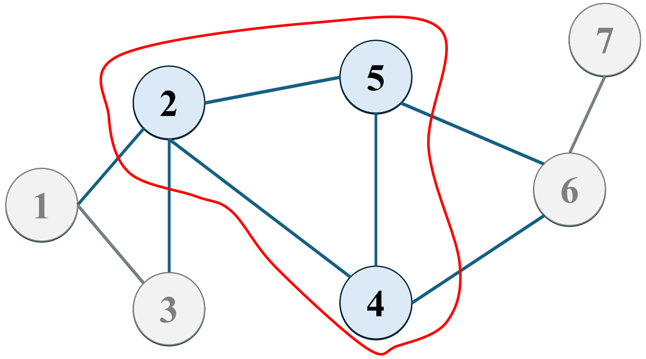
Game theory-based **defense strategies** against coordinated attacks on multi-state interdependent critical infrastructures



POLITECNICO MILANO 1863 LASAR[3]

2. Hybrid Approach to Model Interdependencies

2.2 Multi-state DIIM



$\theta^i = (\theta^i_2, \theta^i_4, \theta^i_5)$

$\theta^i = (0.1, 0.6, 0.3)$

$\gamma^i = (\gamma^i_2, \gamma^i_4, \gamma^i_5)$

$\gamma^i = (0.6, 0.1, 0.3)$

Node	Attack success probability (p^i_k)
2	14.29%
4	85.71%
5	50%

Each strategy defines 2^K possible failure scenarios. For each scenario s:

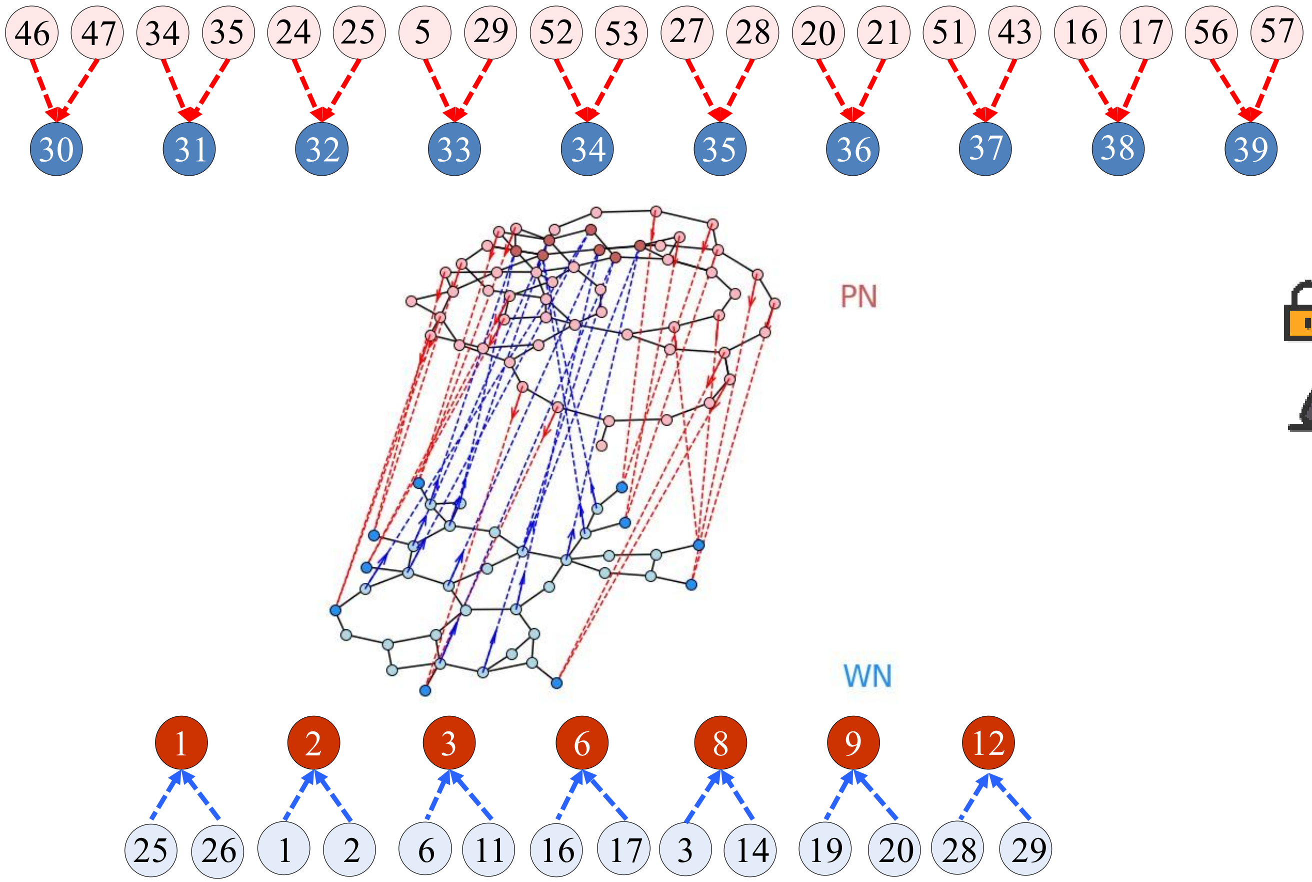
$$u_{a(s)} = O_{SoS}$$
$$u_{d(s)} = 1 - O_{SoS}$$

CPT ranks and weighs scenario utilities based on perceived risk, computing cumulative prospect values for each player

$$V_a(\theta^i)$$
$$V_d(\gamma^i)$$

PSO iteratively explores different θ^i, γ^i to optimize the defender's CPV while considering the attacker's best response

Water Network relies on Power Network for *pumping operations*



Power Network relies on Water Network for *cooling processes*

$l = 0.92 \rightarrow$ The attacker is risk-seeking over losses

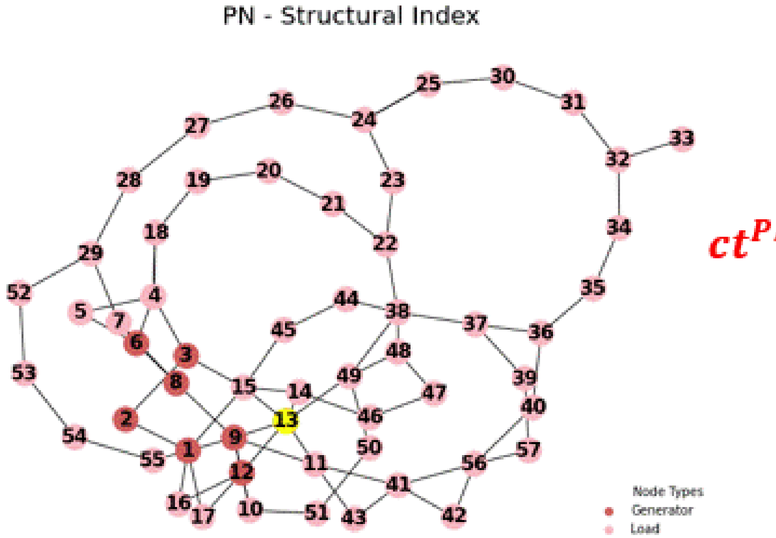
Undervalue small loses and may take aggressive actions even when risky

$g = 0.89 \rightarrow$ The defender is risk-averse over gains

Prefers safer gains and avoids risky strategies even if potentially rewarding

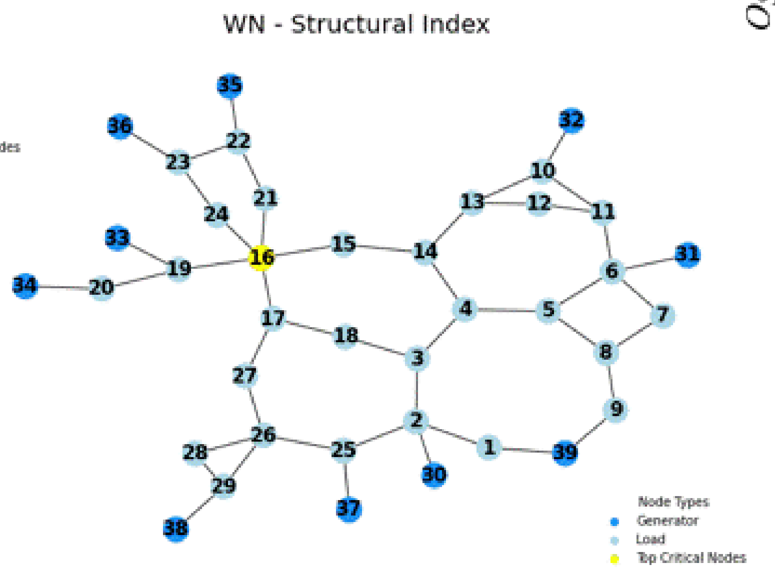
2. Hybrid Approach to Model Interdependencies

2.2 Multi-state DIIM



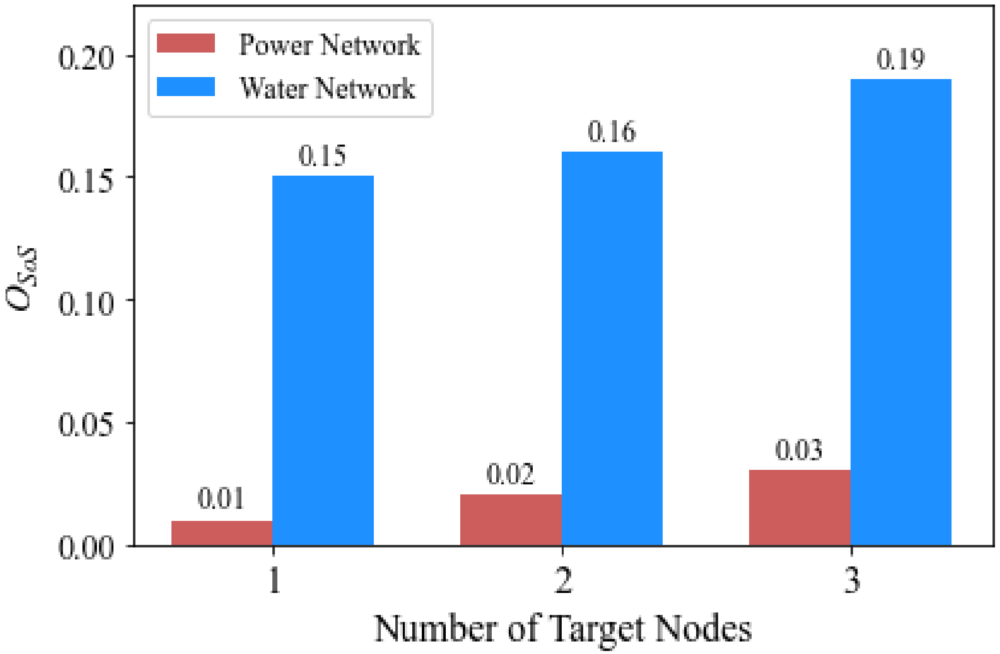
Node importance varies by metric, reinforcing the need to combine centrality measures

$$ct^{PN} = \{n_{13}^{PN}\}$$



$$ct^{WN} = \{n_{16}^{WN}\}$$

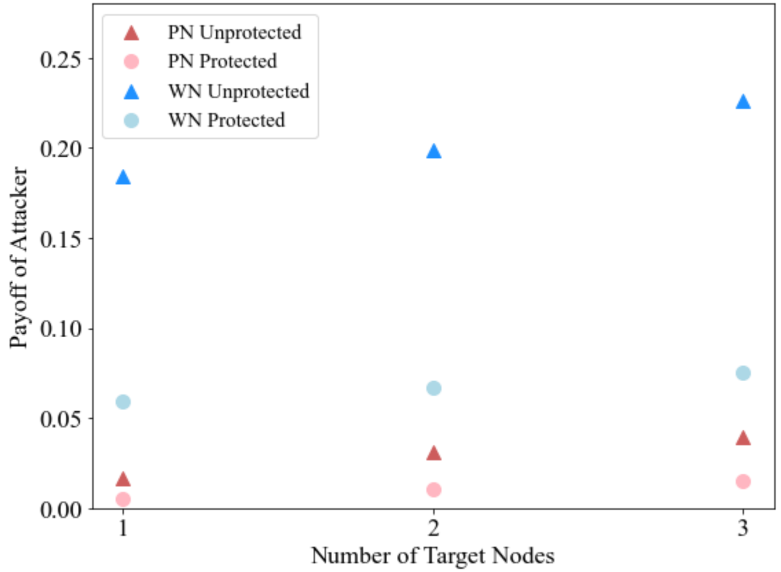
System-of-systems inoperability



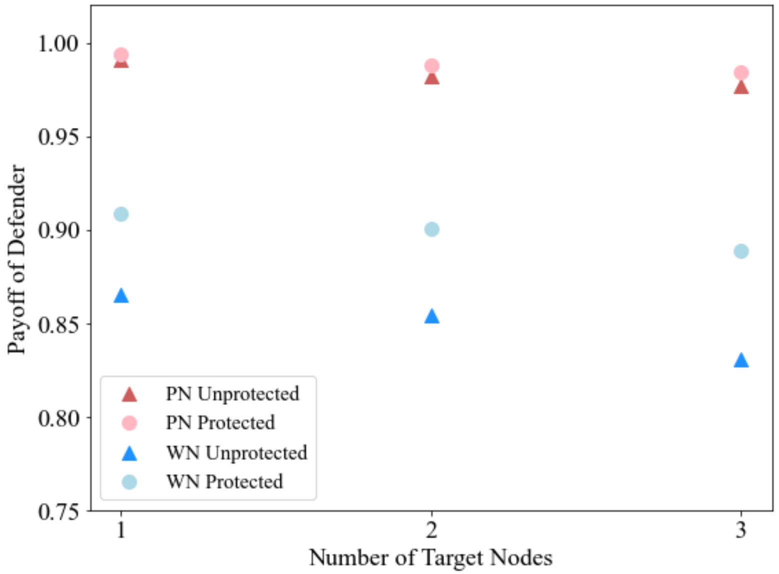
Attacks on the WN lead to higher inoperability than those on the PN

2. Hybrid Approach to Model Interdependencies

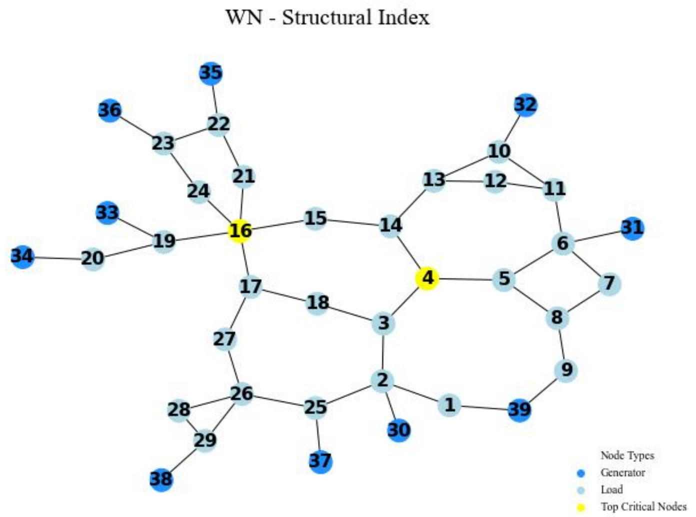
2.2 Multi-state DIIM

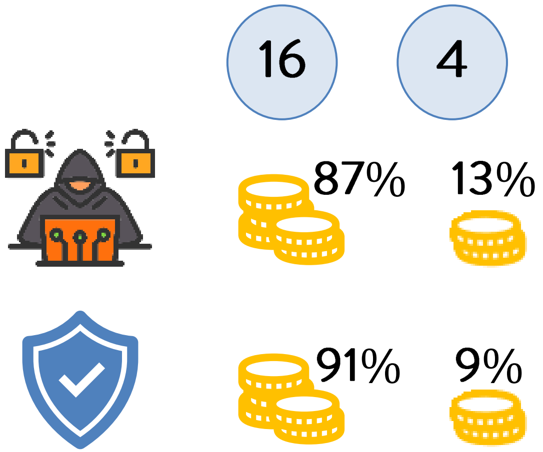


The attacker consistently gains more from targeting the WN than the PN



When no CI is protected, the attacker's payoffs are significantly higher





2. Hybrid Approach to Model Interdependencies

2.2 Multi-state DIIM

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Dynamic inoperability input-output modeling of a system of systems made of multi-state interdependent critical infrastructures

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Stavanger ESREL SRA-E 2025

Inoperability Assessment of Interdependent Critical Infrastructures by Minimal Inoperability Sets Analysis

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Game theory-based defense strategies against coordinated attacks on multi-state interdependent critical infrastructures

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3. Exam Preparation Exercises

Instructions

- The exam consists of 2 exercises (E), 4 multiple-choice questions (MQ) and 3 open questions (Q);
- The total score of the exam is 30 points, and the minimum score to pass is 18;
- The duration of the exam is 2 hours and 30 minutes.

Exercise 1.

[10 points]

Consider a **fire protection system** that may malfunction either because the fire detection system fails or because the water deluge system fails.

The fire detection system fails when both the smoke detector and the heat detection fail.

The water deluge system fails when either the pump fails, or the nozzles are blocked.

a) Build the Fault Tree with top event "fire protection system malfunction", assuming the basic events listed in the table.

b) List the Minimal Cut Sets (MCS).

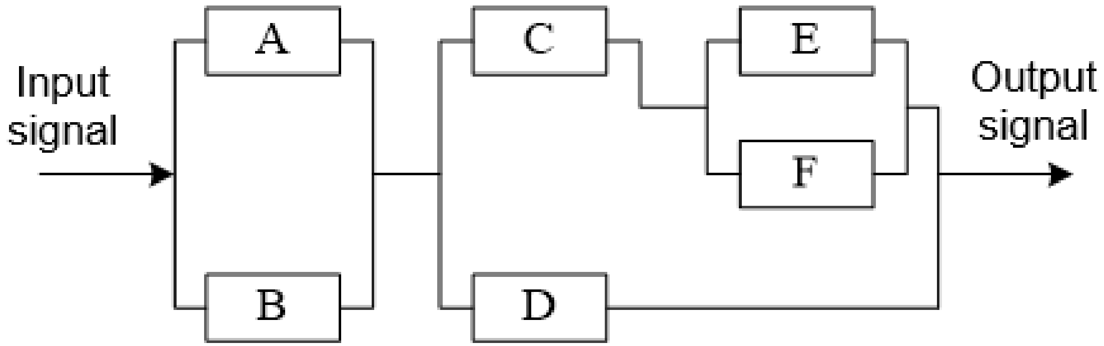
c) Calculate the 1-year probability of the top event "fire protection system malfunction".

Events	Probability (over 1 year)
Smoke detection failure	5×10^{-4}
Heat detection failure	5×10^{-2}
Pump failure	5×10^{-7}
Nozzles blocked	5×10^{-8}

Exercise 1.

[10 points]

Consider the following logical structure of a cyber control system, composed by six components (A,B,C,D,E,F). The system is functioning when an input signal is processed throughout the system and an output is delivered.



a) Build the Fault Tree corresponding to the top event: ‘no output is delivered’.

b) List the Minimal Cut Sets (MCS).

c) Assume that each component has a constant failure rate $\lambda = 1 \times 10^{-4}$/hour and compute the reliability of the system at $t = 1000$ hours.

Exercise 1.

[10 points]

A successful heat detection by a heat detector actuates the automatic foam sprinklers of a fire spread control system. If the sprinklers are successfully activated, the fire is considered controlled.

However, if the sprinklers fail, the fire is not controlled unless fire brigades—automatically alerted—can reach the room before severe damage occurs and extinguish the fire using available fire extinguishers, which

a) Build the Event Tree considering the initiating event "Fire spread", using the events headers: Fire detection, Sprinklers actuation, Fire brigade intervention and Extinguishers availability.

b) Compute the probability of the fire control system success, assuming the probability of each event are as listed in the table

Events	Probability
Fire detector failure	8×10^{-4}
Sprinklers actuation failure	2×10^{-4}
Fire brigade intervention failure	5×10^{-4}
Extinguishers availability failure	4×10^{-3}

Exercise 2.

[10 points]

Consider a continuously monitored component with constant failure $\lambda = 0.003$h-1

The component starts ON at time $t = 0$. The mission time is $T = 100$h.

Estimate the reliability of component using the following random numbers of failure time.

Trail	Random number
1	0.20
2	0.85
3	0.10
4	0.50
5	0.95

Multiple answer

[1 point]

Multiple answer

[1 point]

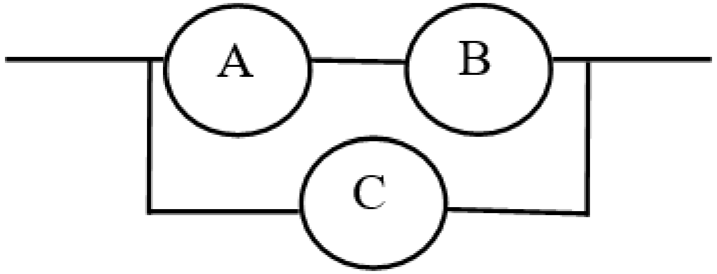
Which one of the following sentences is not one of the tasks to be typically performed to carry out a Risk Assessment?

a) System description and modelling
b) Historical analysis of past accidents
c) Uncertainty and Sensitivity Analysis
d) Selection of most critical hazards and identification of initiating events

Multiple answer

[1 point]

For the system sketched in the figure, which among the following events is a Minimal Cut Set?



a) $\bar{C}$ **b)** $\overline{AB}$ **c)** $\overline{ABC}$ **d)** $\overline{AC}$

Which topological centrality measure can be used to identify the nodes in a network that, on average, require fewer steps to communicate with other nodes?

a) Degree centrality
b) Closeness centrality
c) Information centrality
d) Betweenness centrality

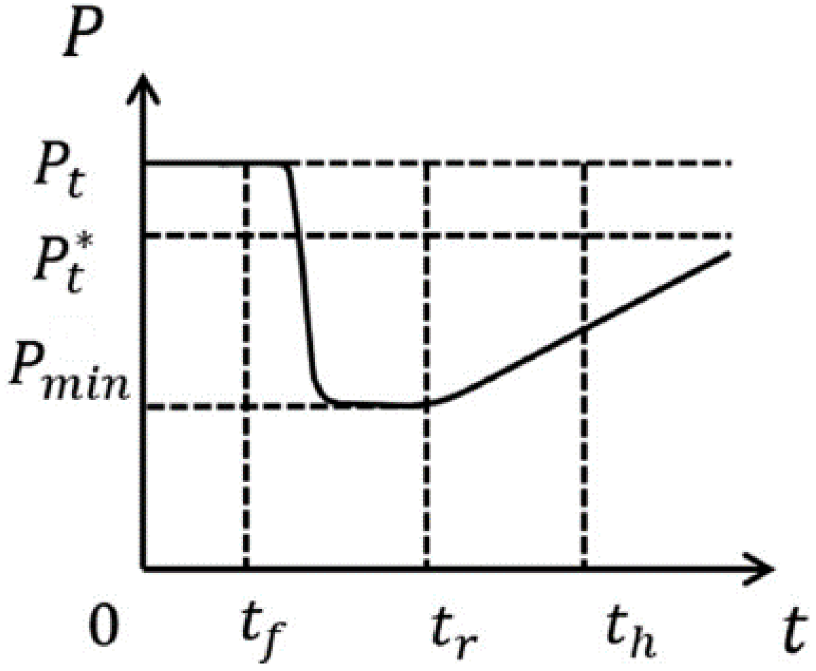
Multiple answer

[1 point]

For a system with performance $P(t)$, as shown in the figure, where: P_t is the nominal performance, P_t^* is the minimum acceptable performance, P_{min} is the minimum reached performance, and t_h is the maximum allowed recovery time, a failure occurs at time t_f and recovery begins at time t_r.

Which one of the following statements is correct?

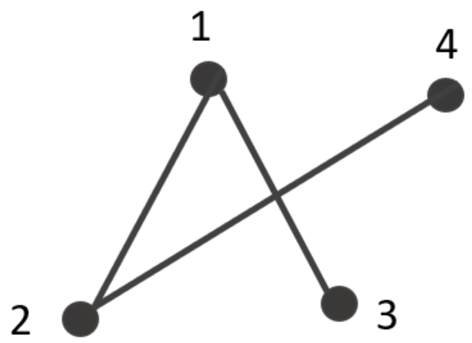
a) The recovery of the system is effective
b) The system can absorb the disruption event
c) The system is not resilient
d) The system is resilient



Multiple answer

[1 point]

Which one is the adjacency matrix of the graph represented in the figure?



$$\begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

a)

$$\begin{bmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix}$$

b)

$$\begin{bmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

c)

$$\begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 1 & 1 \\ 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

d)

Which one is correct about Value at Risk (VaR) and Conditional Value at Risk (CVaR)?

a) CVaR is a conservative approximation of VaR
b) CVaR is difficult to optimize numerically when losses are not normally distributed
c) VaR is superior to CVaR in risk optimization
d) VaR preserves convexity and can be expressed as a minimization formulation

Open questions

[2 points]

Compare complicated and complex systems, providing 3 characteristics for each type of system

Open questions

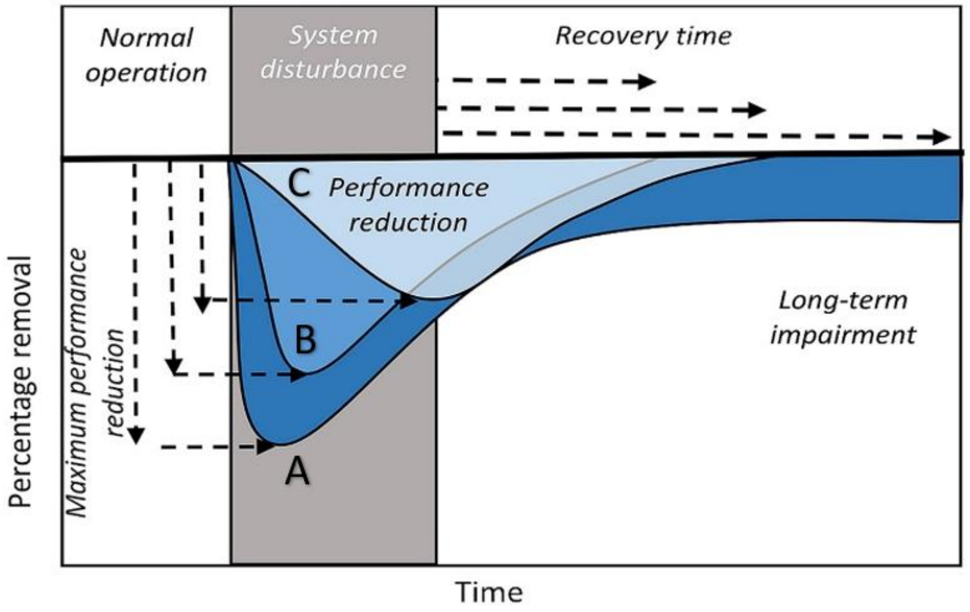
[2 points]

Discuss the objective of the resilience assessment of a system and three different resilience assessment methods

Open questions

[2 points]

Based on the performance curves shown in the figure, where the same disruption scenario occurs for three systems (A, B, C), compare and discuss the resilience of the systems A, B, C.



Discuss advantages and limitations of the Fault Tree method

Open questions

[2 points]

Define the term ‘Resilience’ in the context of system performance

THANKS

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