



MODELING FOR CRITICAL INFRASTRUCTURES PROTECTION AND RESILIENCE

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Content

- Critical infrastructures
- Modeling reasons
- Modeling issues
- Modeling methods
- Conclusions

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Critical infrastructures

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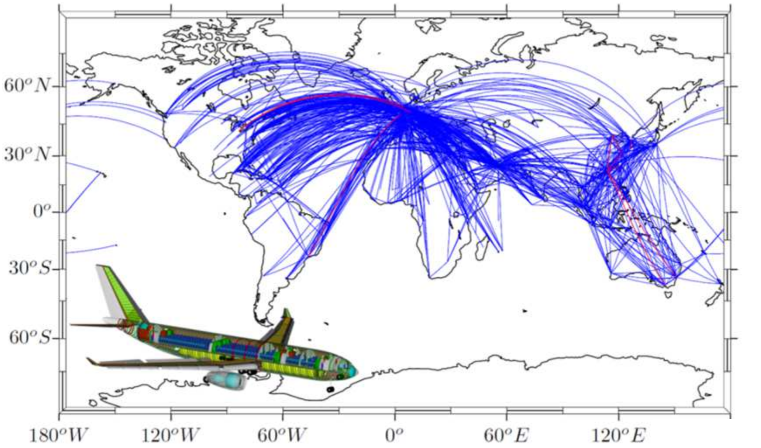
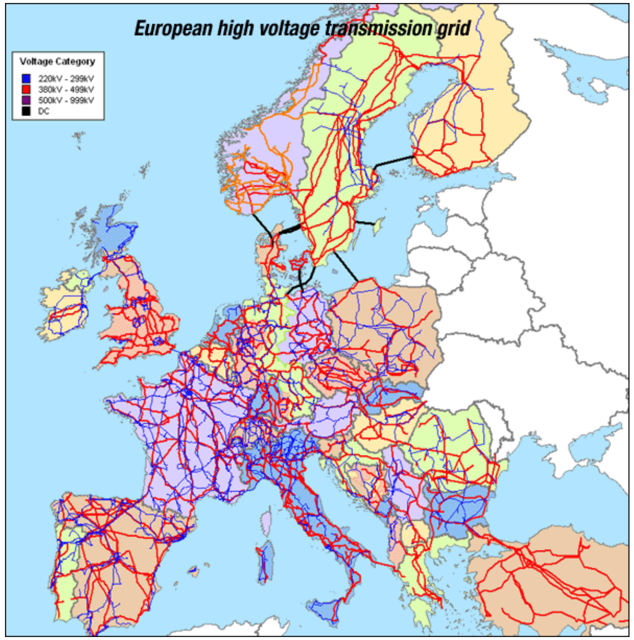
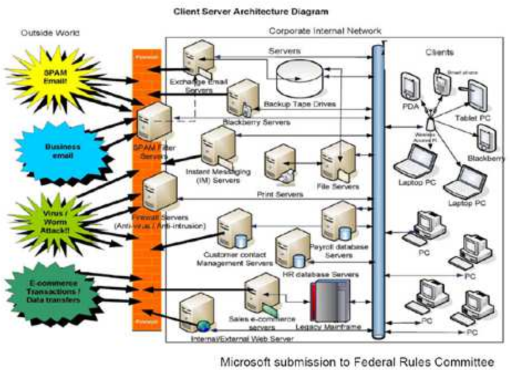
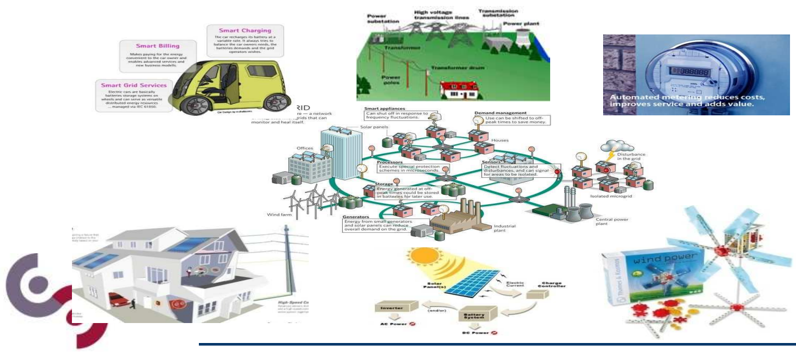
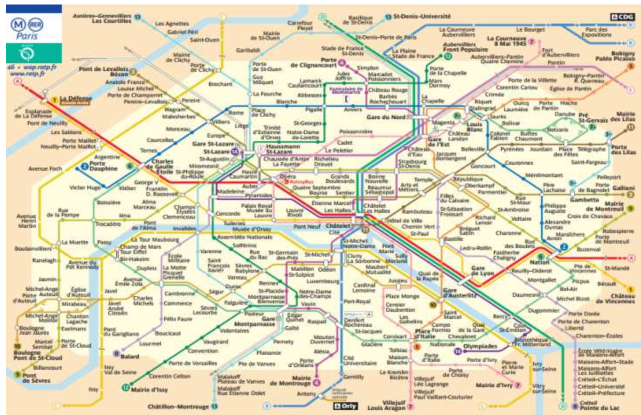


__Critical__ infrastructures (CIs)









Statement (obvious):

Critical Infrastructures are

(Engineered) Complex Systems

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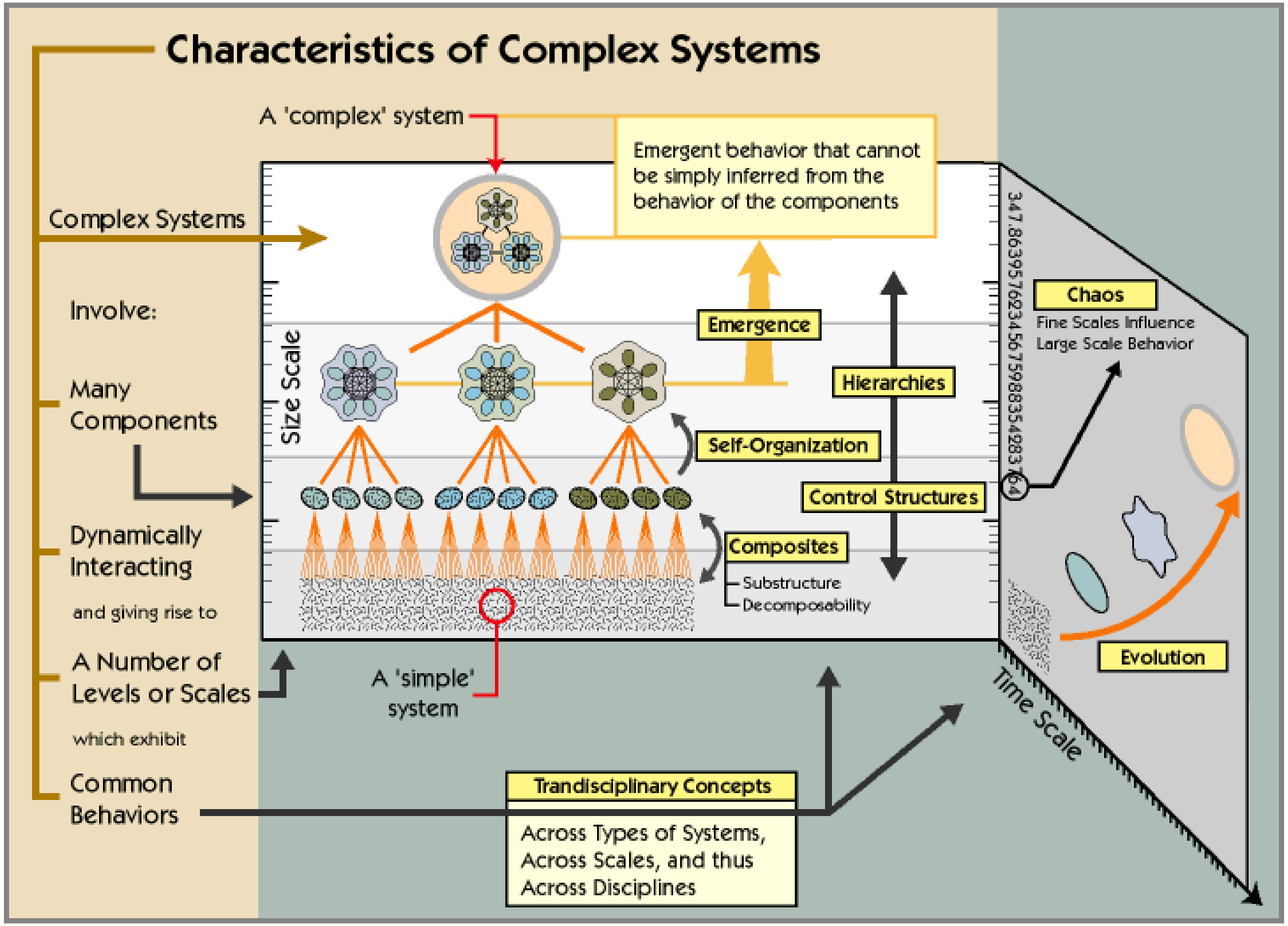
Complex Systems

Complex (technical) systems

- Network of many interacting components
- Components of heterogeneous type
- Hierarchy of subsystems
- Interactions across multiple scales of space and/or time

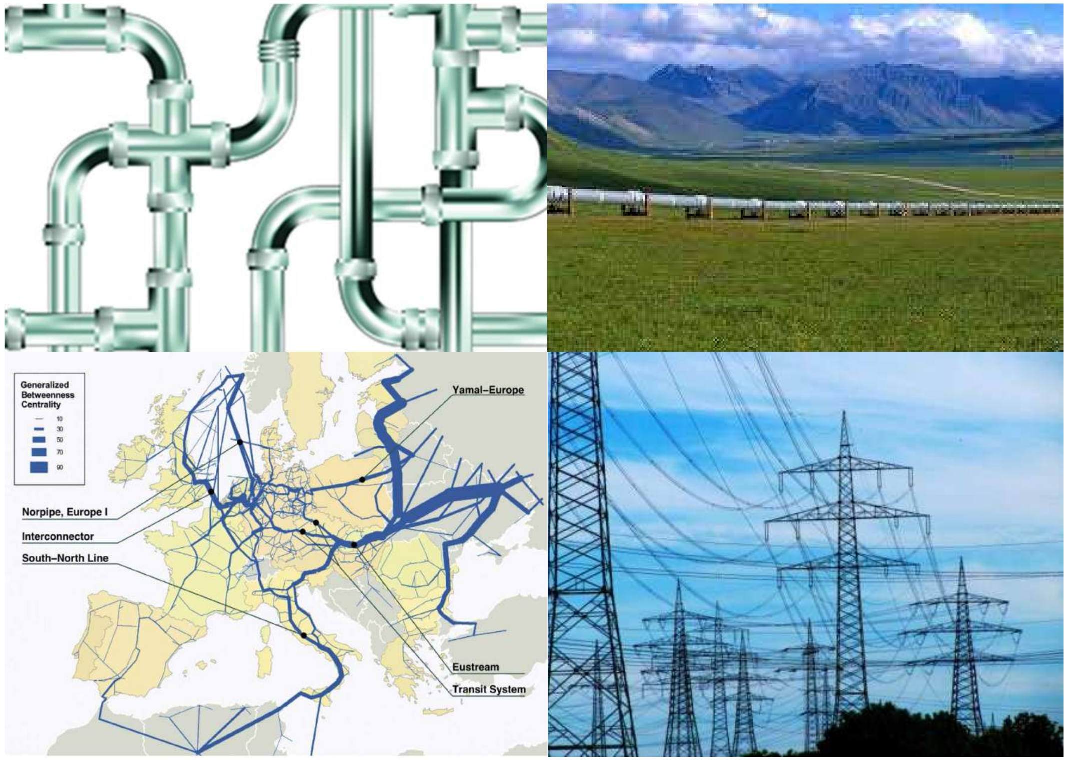
Dependences (uni-directional) and interdependences (bi-directional)

Characteristics of complex systems



[New England Complex Systems Institute, 2005]

Critical infrastructures = complex systems

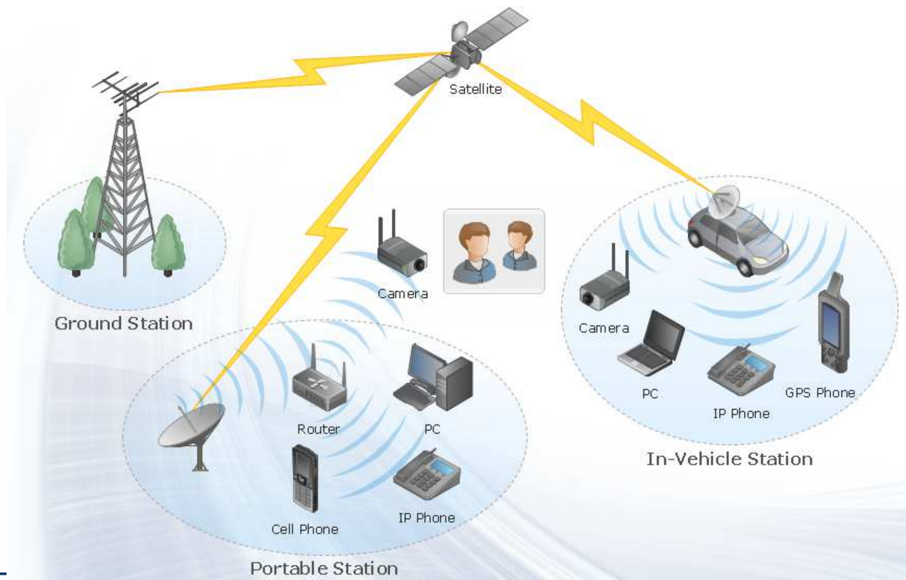


- Structural complexity
  - Heterogeneity
  - Scale and dimensionality (interdependences)
  - Decomposability

- Dynamic complexity
  - Emergent behavior
  - Adaptive learning
  - Evolution and growth mechanisms

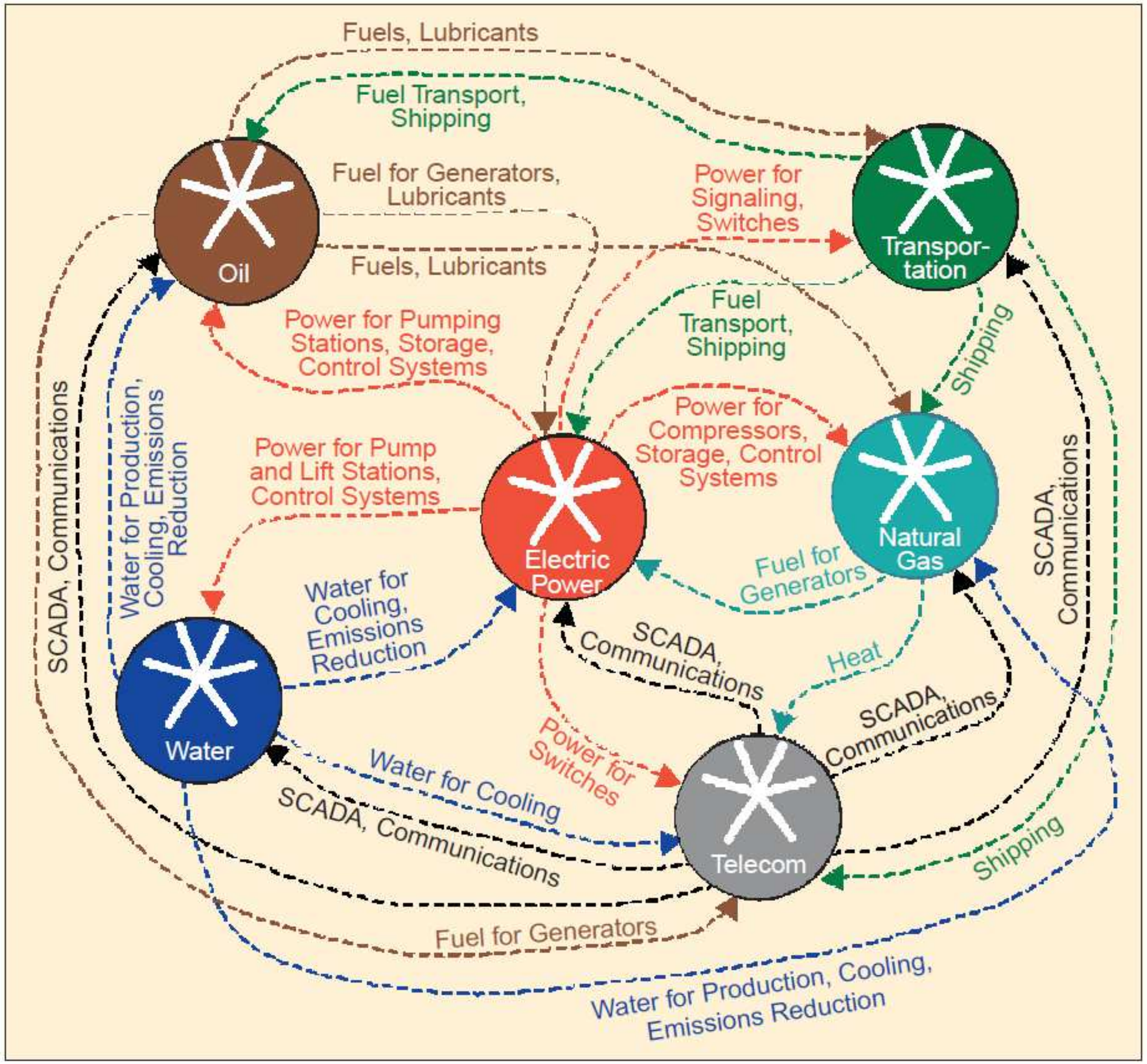
Critical Infrastructures: structural complexity

- ***Heterogeneity*** of components across different technological domains due to increased integration among systems.
  - ❖ Physical hard components (road, railways, pipelines, …)
  - ❖ Soft components (SCADA, information and telecommunication systems)
  - ❖ Human and organizational components



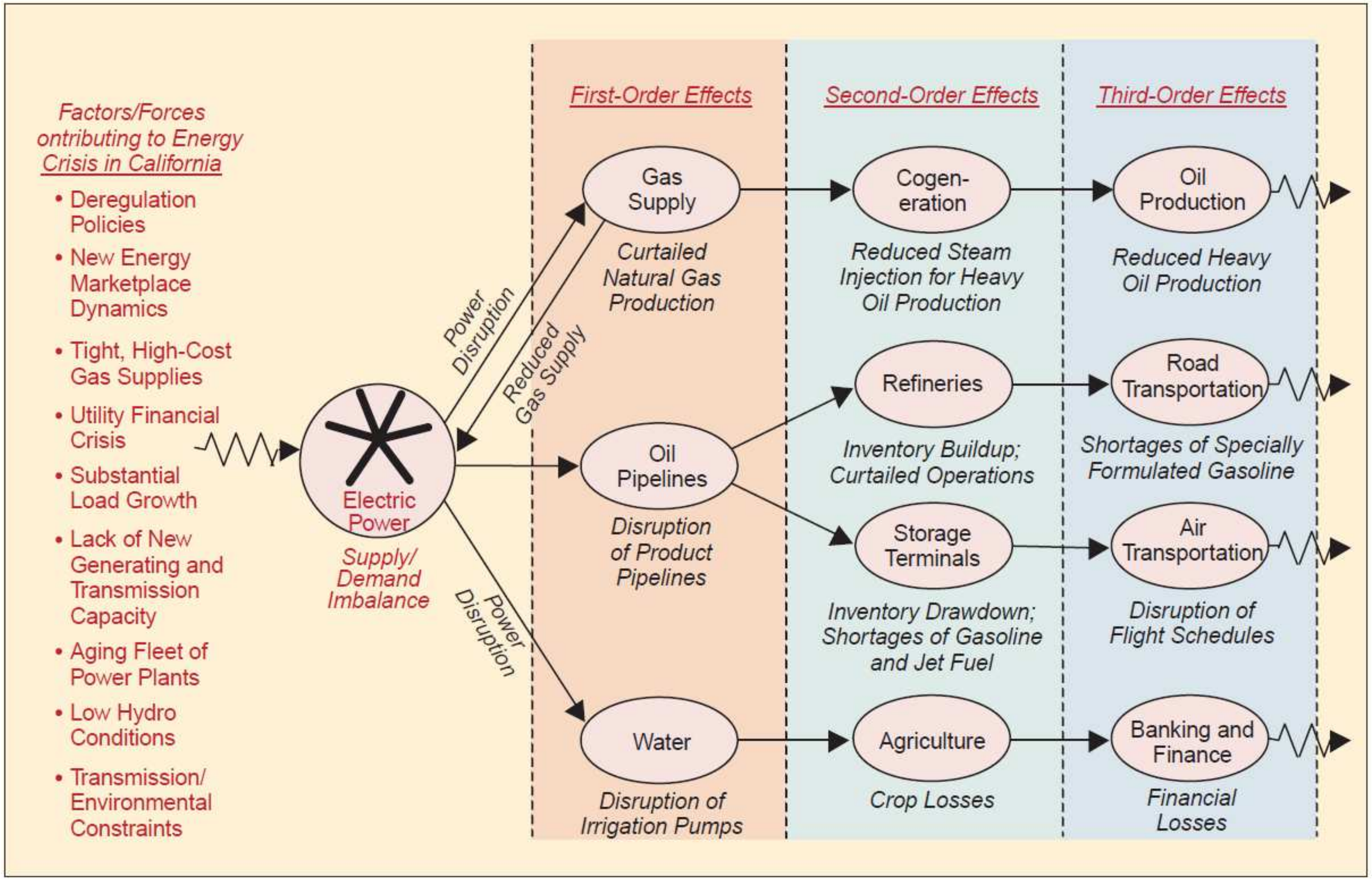
Example of infrastructures **interdependencies** [Rinaldi et al. 2001]

(**systems of systems**)



Critical Infrastructures: structural complexity

Examples of nth-order interdependencies and effects.



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Critical Infrastructures: dynamic complexity

Emergent behavior refers to actions of a system as a whole that are not simple combinations of the actions of the individual constituents of the system. It emerges in response to changes in the environmental and operational conditions of parts of the system.

Examples:

- *Internet*: social bookmarking leads to an emergent effect in which information resources are reorganized according to users priorities.
- *Electric power grids*: local failures can evolve into unexpected cascade failure patterns with transnational, cross-industry effects.
- *Smart grids*: large amount of information exchanged within technologies at a period of high electricity demand can lead to a vulnerable condition of the system.
- *Road transportation congestion*: slow movement of the traffic.

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Critical Infrastructures: dynamic complexity

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Emergent behavior: Traffic

Global system property that emerges: **slow movement of the traffic**

It **arises from** the cumulative effects of the actions and interactions of all individual vehicles. The global effects depend on the general activities of sufficiently many of them, within the context of that highway.

It is **not due to** specific actions of individual vehicles → no individual vehicle plays a critical role.
If some subset of the vehicles acted differently in their local actions (within certain boundaries), the global effect of slow-moving traffic would be unchanged.

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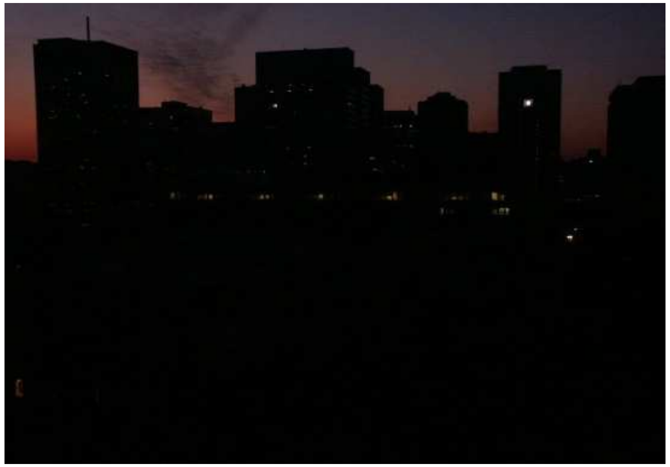
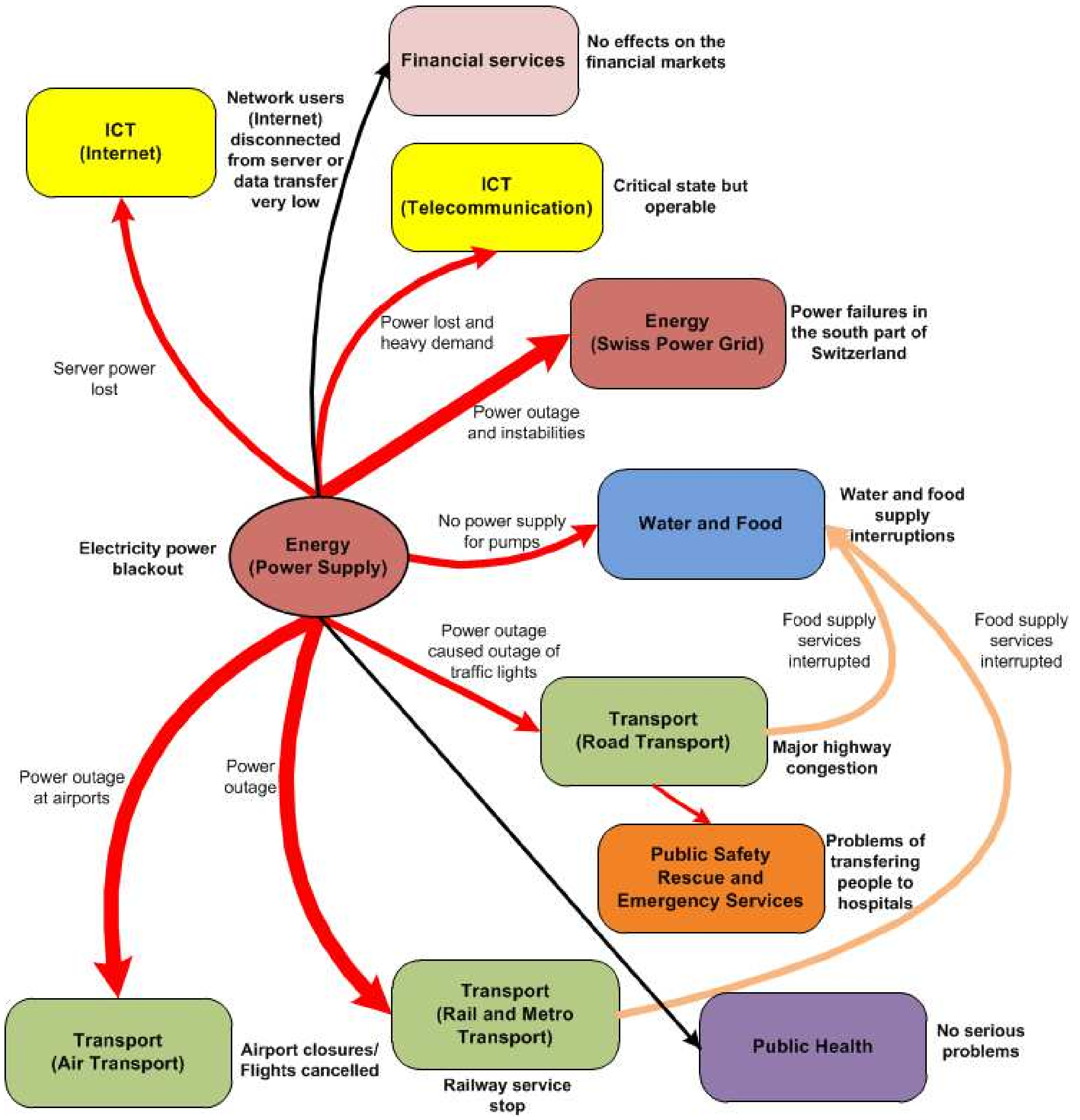
The problem

What problem?

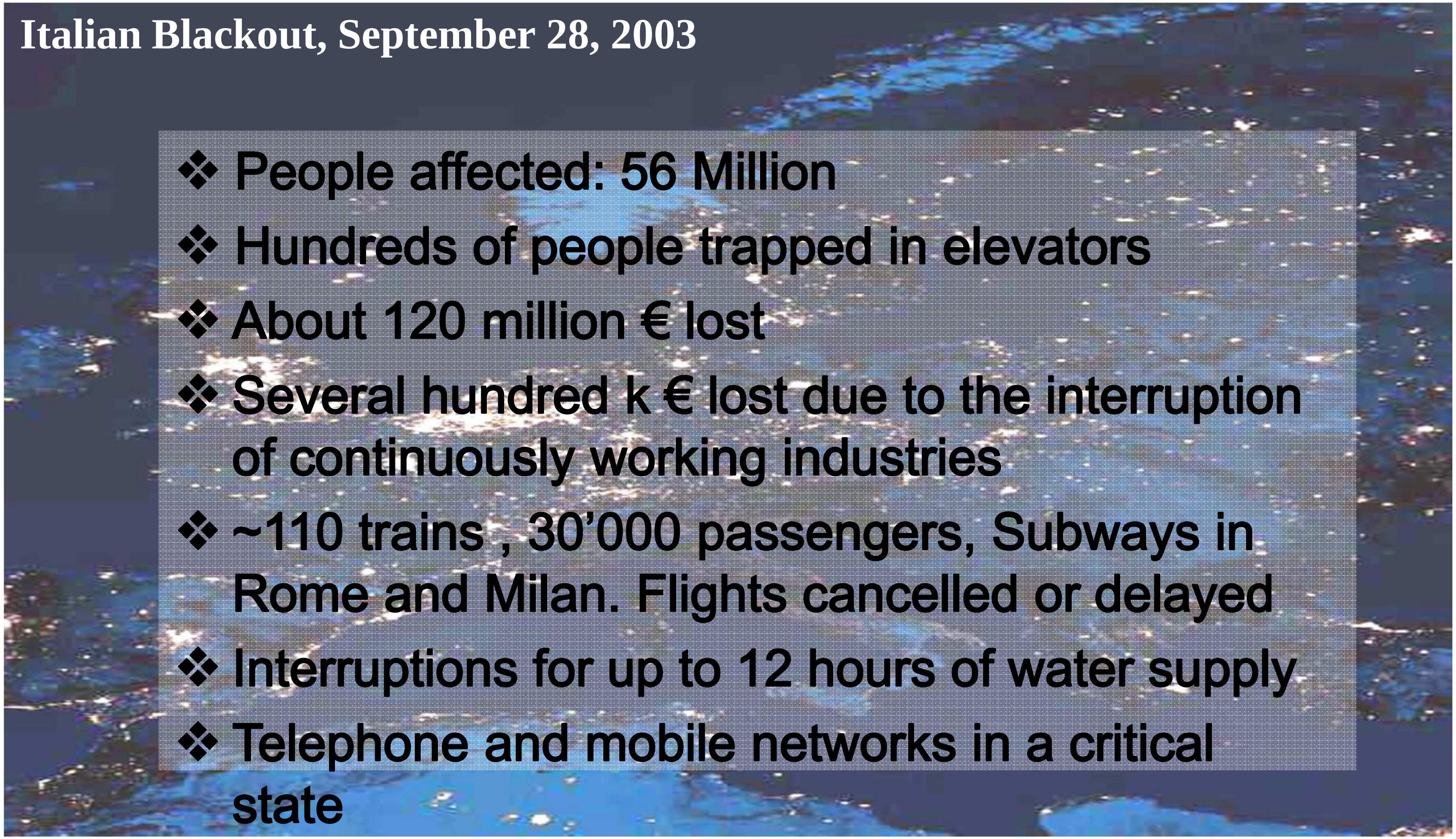


cascading failures

Italian Blackout, September 28, 2003



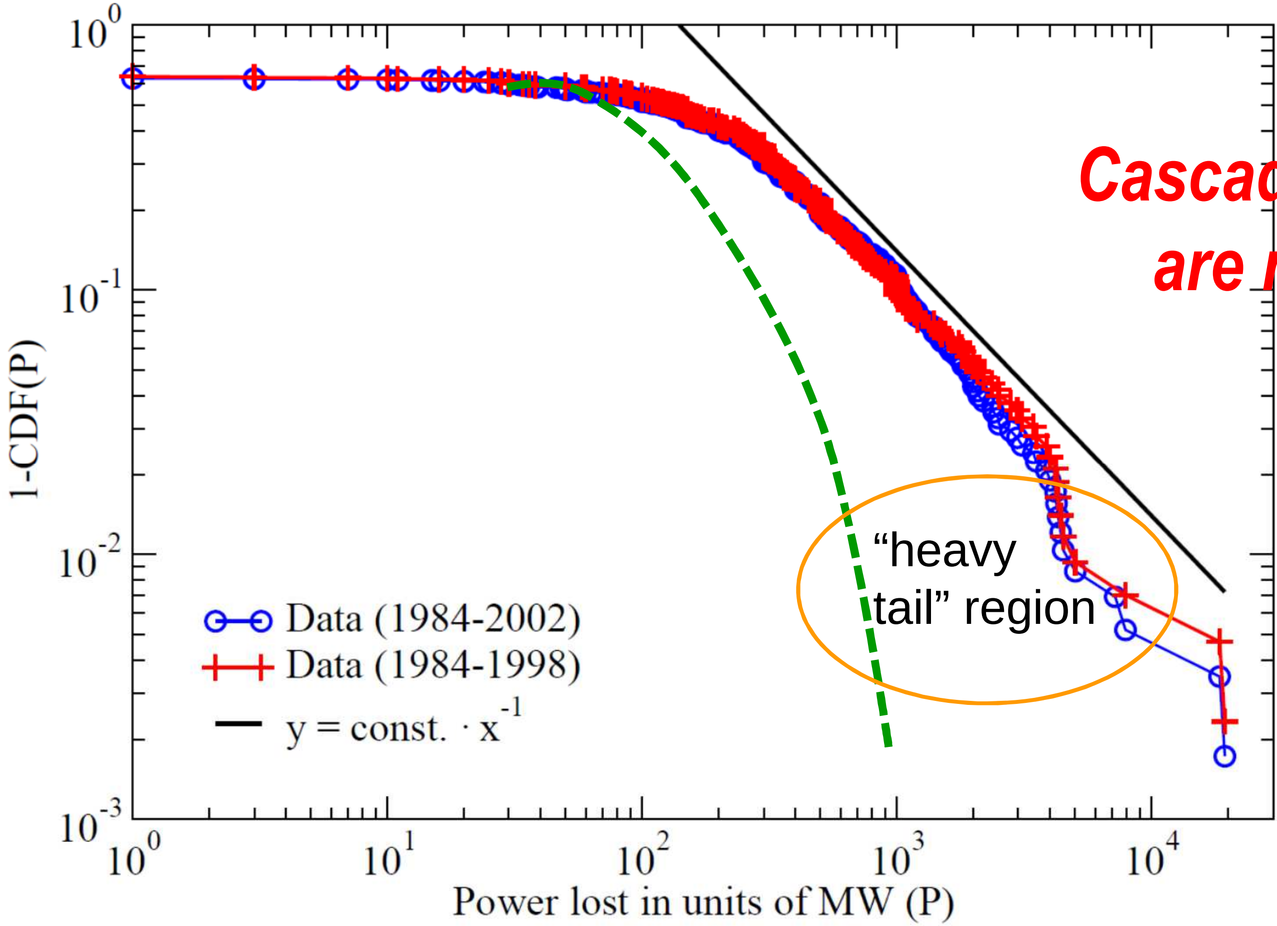
Relevance of the problem: large consequence



Italian Blackout, September 28, 2003

- ❖ People affected: 56 Million
- ❖ Hundreds of people trapped in elevators
- ❖ About 120 million € lost
- ❖ Several hundred k € lost due to the interruption of continuously working industries
- ❖ ~110 trains , 30’000 passengers, Subways in Rome and Milan. Flights cancelled or delayed
- ❖ Interruptions for up to 12 hours of water supply
- ❖ Telephone and mobile networks in a critical state

Relevance of the problem: non-negligible probability



Cascading failures are not 'rare'!

(Weron et al., 2006)

Relevance of the problem

Cascading failures

Large consequence

Non-negligible probability

Critical infrastructure protection and resilience (CIPR)

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Resilience

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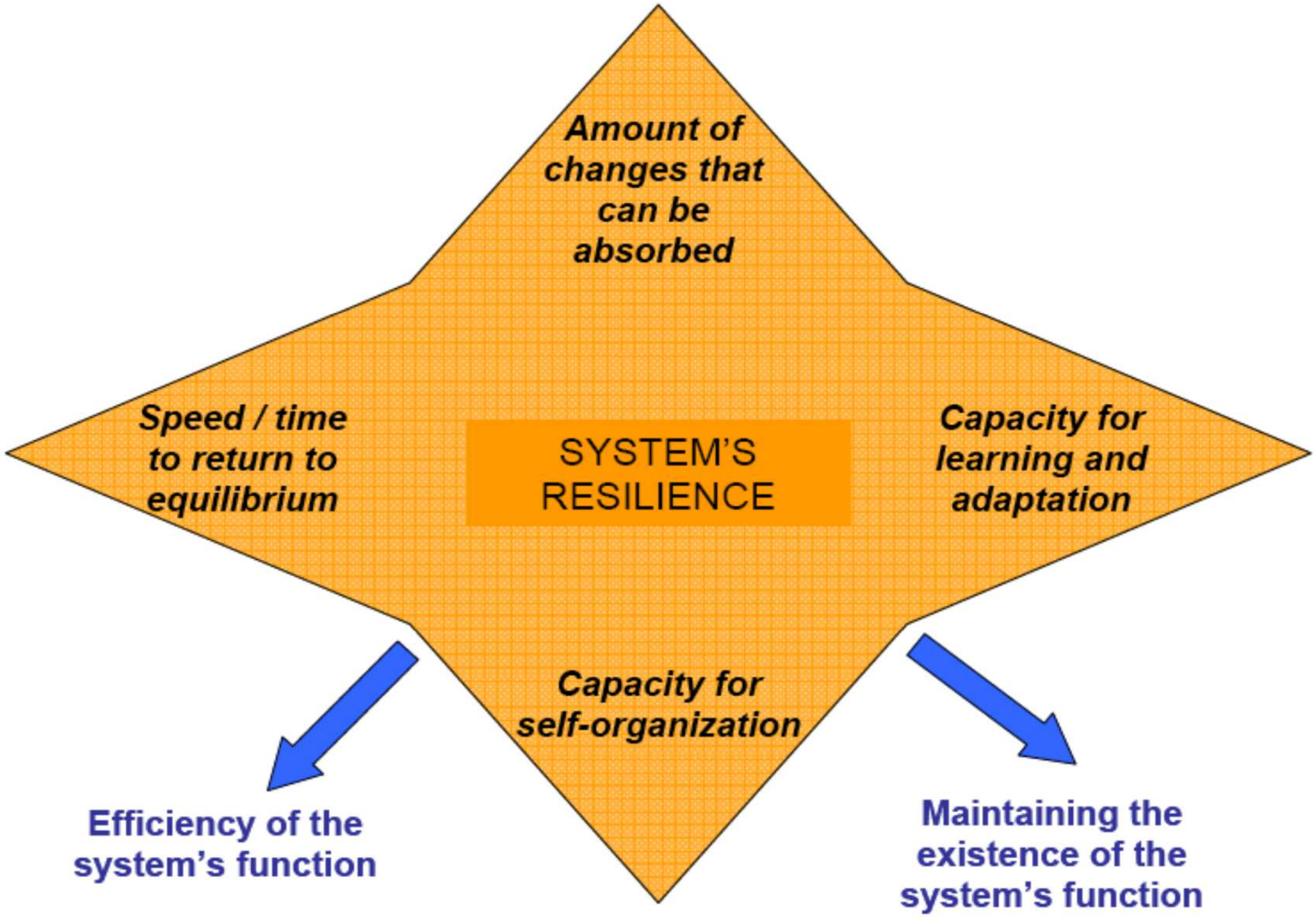
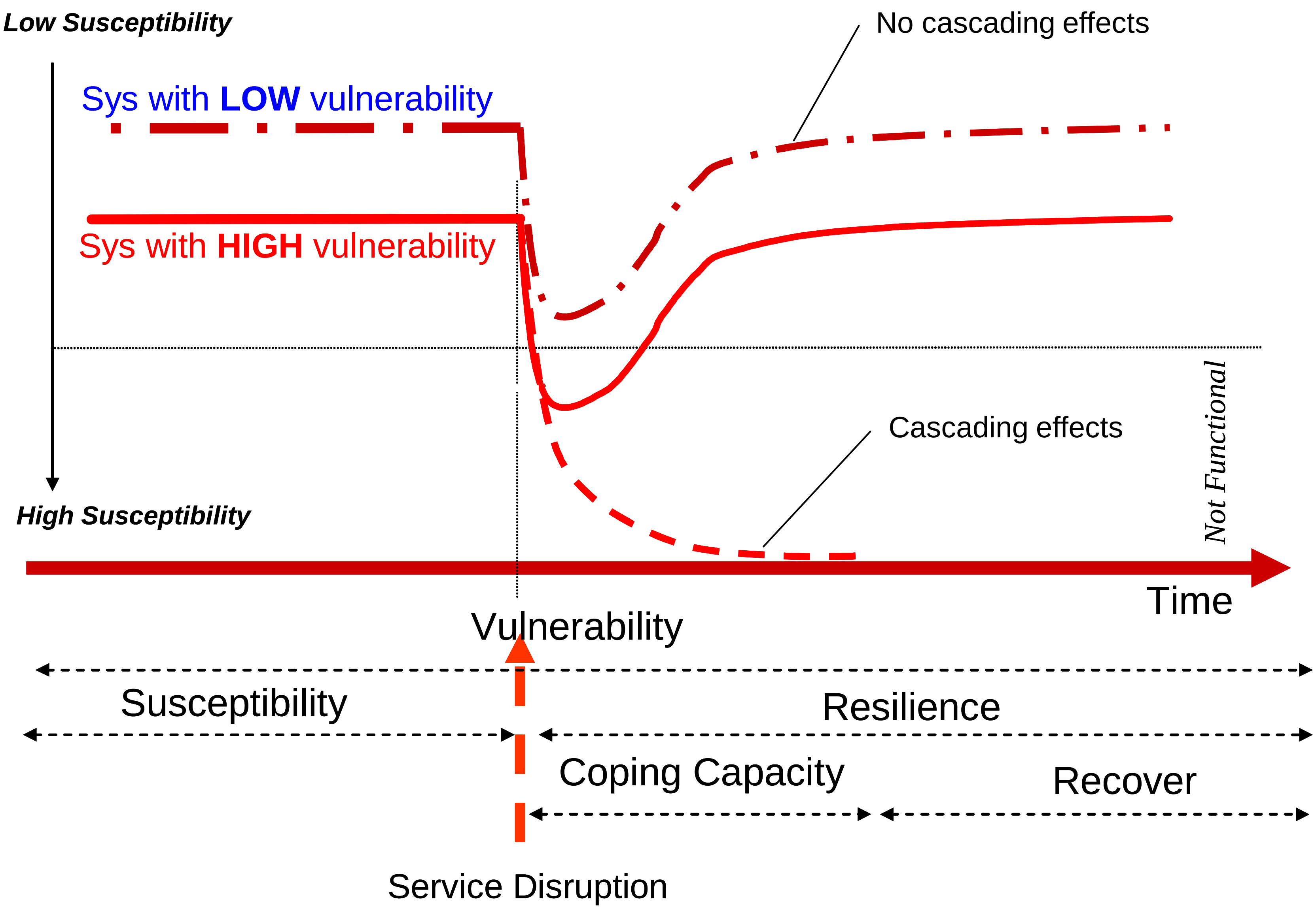
Resilience: ability of the system to sustain or restore its basic functionality following a risk source or event (even unknown events) [SRA, Glossary, Aven, Sept. 2014]. It includes technical (physical), organizational, social and economic aspects [Bruneau et al. 2003]

Features of system's resilience



Vulnerability and resilience



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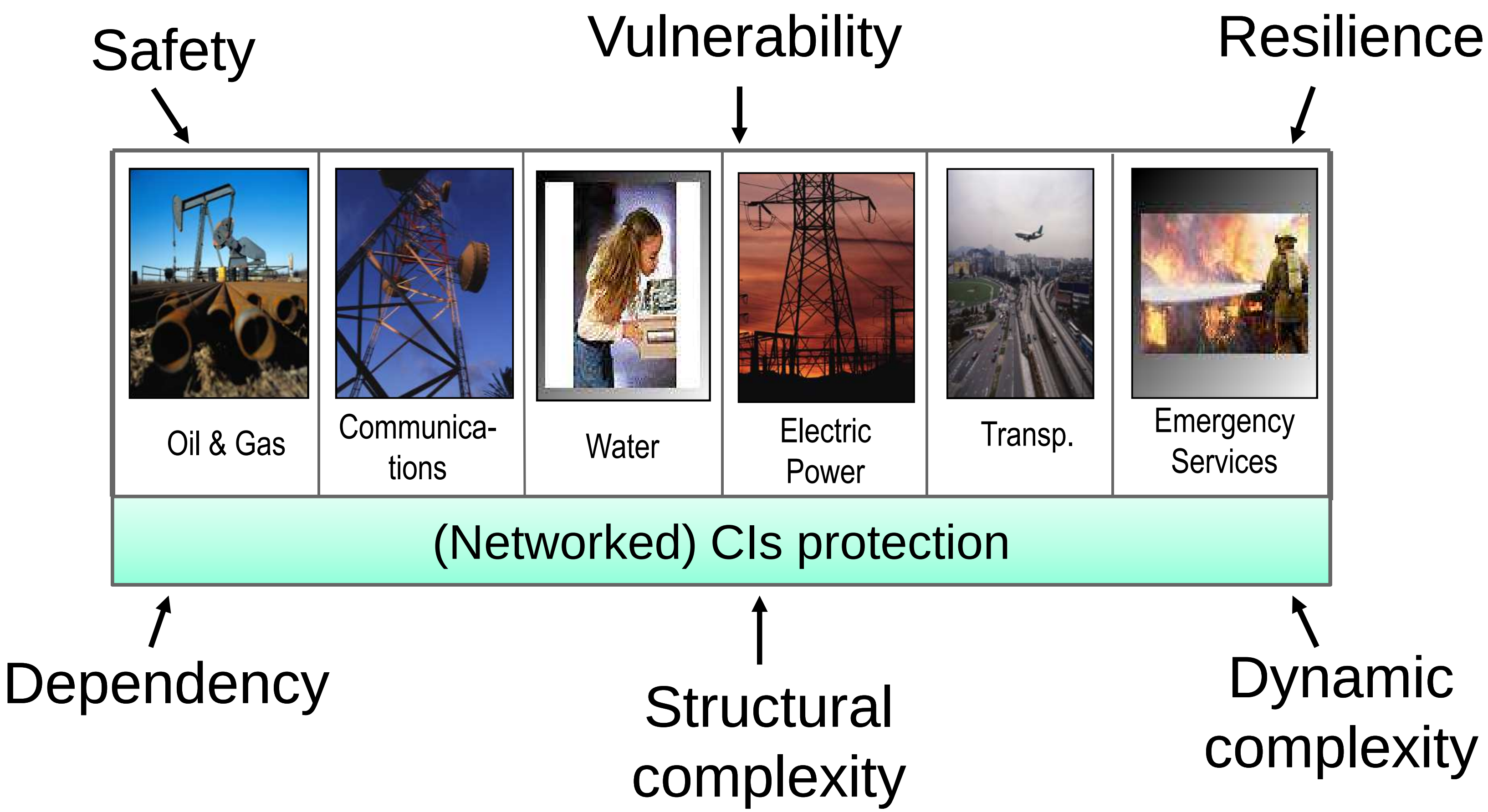
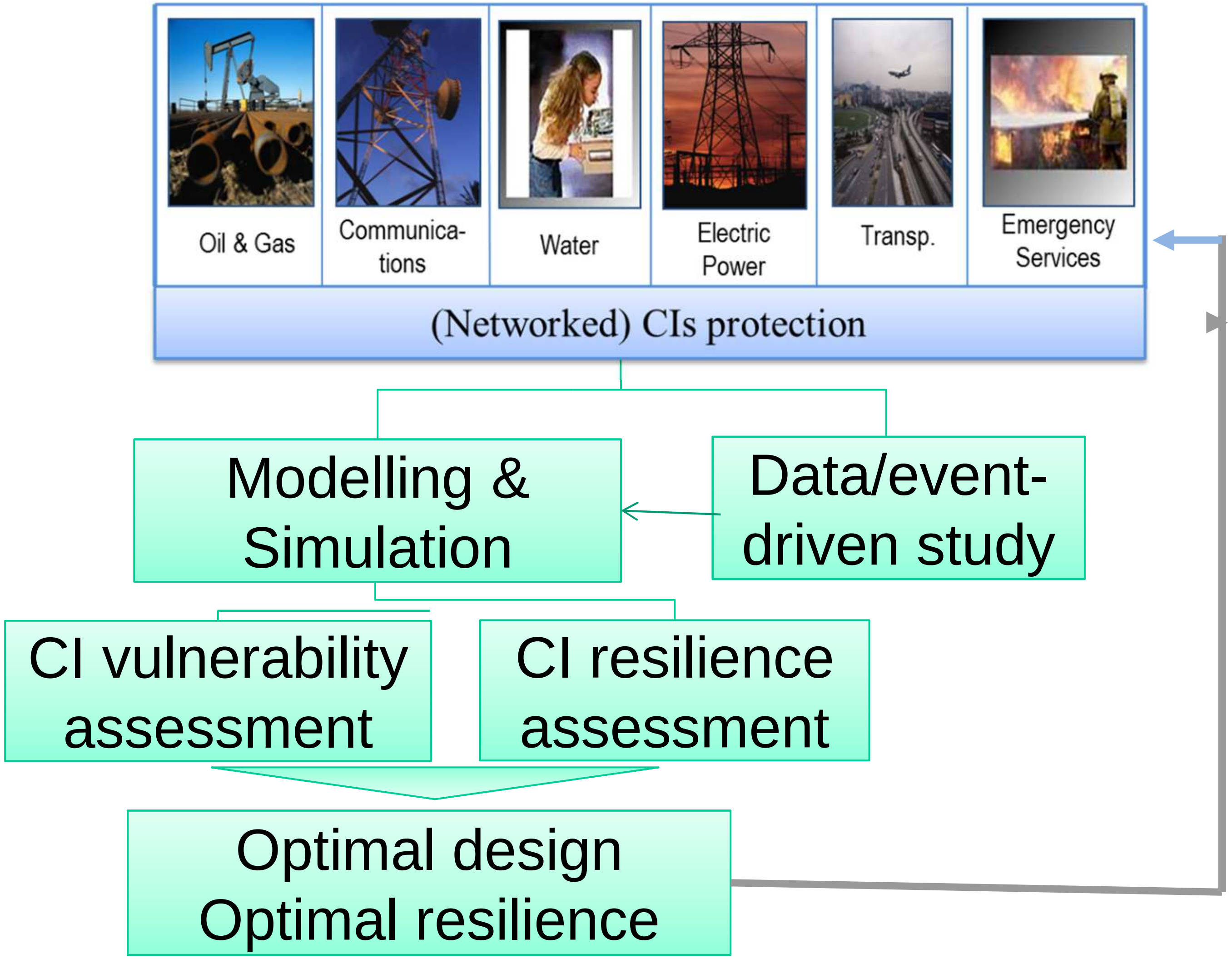
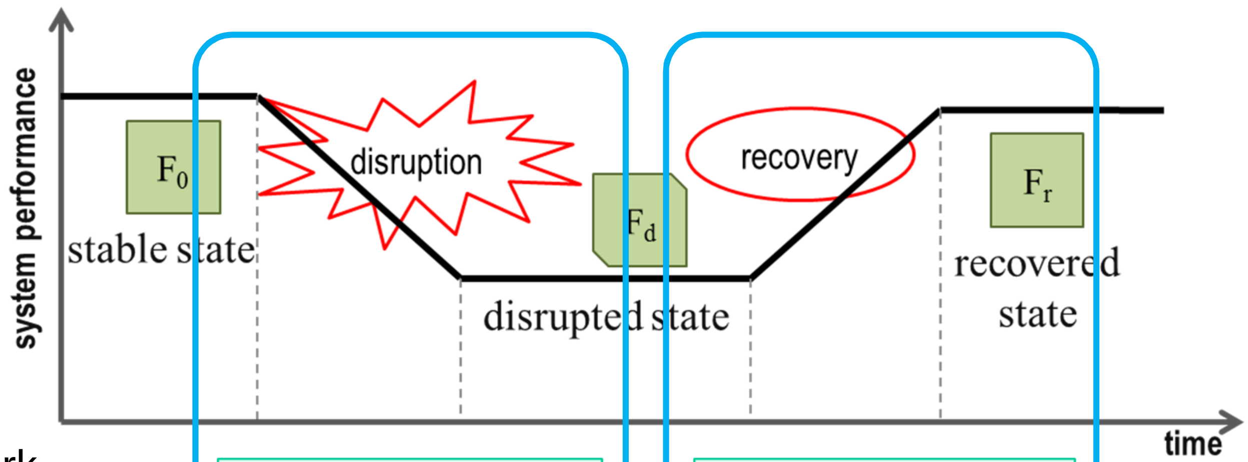


Safety
Vulnerability
Resilience
Oil & Gas
Communica-tions
Water
Electric Power
Transp.
Emergency Services
(Networked) CIs protection
Dependency
Structural complexity
Dynamic complexity

Protection and resilience of critical infrastructures: ways to go



Resilience of critical infrastructures



- Network theory-based
- Physical (power) flow

Cascading failure model

↓

Optimal design for cascading failure mitigation

- Multi-objective evolutionary optimization, e.g., NSGA-II, NSBDE…

System restoration model

↓

Optimal restoration for system resilience

- Flow

- Mixed integer programming
- Heuristic searching and project scheduling

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Protection and resilience of critical infrastructures: the analysis

System analysis:

- hazards and threats identification
- physical and logical structure identification
- **dependencies and interdependences** identification and modeling
- dynamic analysis (cascading failures)

Quantification of system safety indicators

Identification of critical elements

Application for system improvements (optimization):

- design
- operation
- interdiction/protection

W. Kroger and E. Zio, *"Vulnerable Systems"*, Springer, 2011

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Modeling for critical infrastructures protection and resilience

- Vulnerability and Resilience assessment of CIs
  - Phenomenological/ Functional methods
    - e.g., Agent Based Modeling and Simulation, System Dynamic Model, Economic-Based Approaches, …
  - Structural/ Topological methods
    - e.g., Topology-based approaches
  - Flow methods
    - e.g., Flow-based approaches (maximum flow model, …)
  - Logical methods
    - e.g., Risk Analysis (fault/event trees, …), Probabilistic Modeling (Markov Chains, Bayesian network, …)

Modeling for critical infrastructures protection and resilience: the Dual Analysis

- **Critical Infrastructures are engineered complex systems: structure + failure dynamics + resilience process**

Direct Problem

Aggregation Challenge

Evaluating Global Indicators

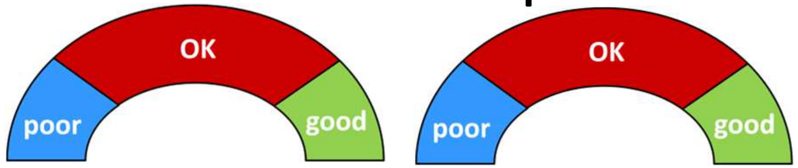
Inverse Problem

Disaggregation Challenge

Identifying Vulnerabilities at the Components Level

- **Critical Infrastructures modeling: topological, flow, phenomenological, logic**

Detail **Computational cost**



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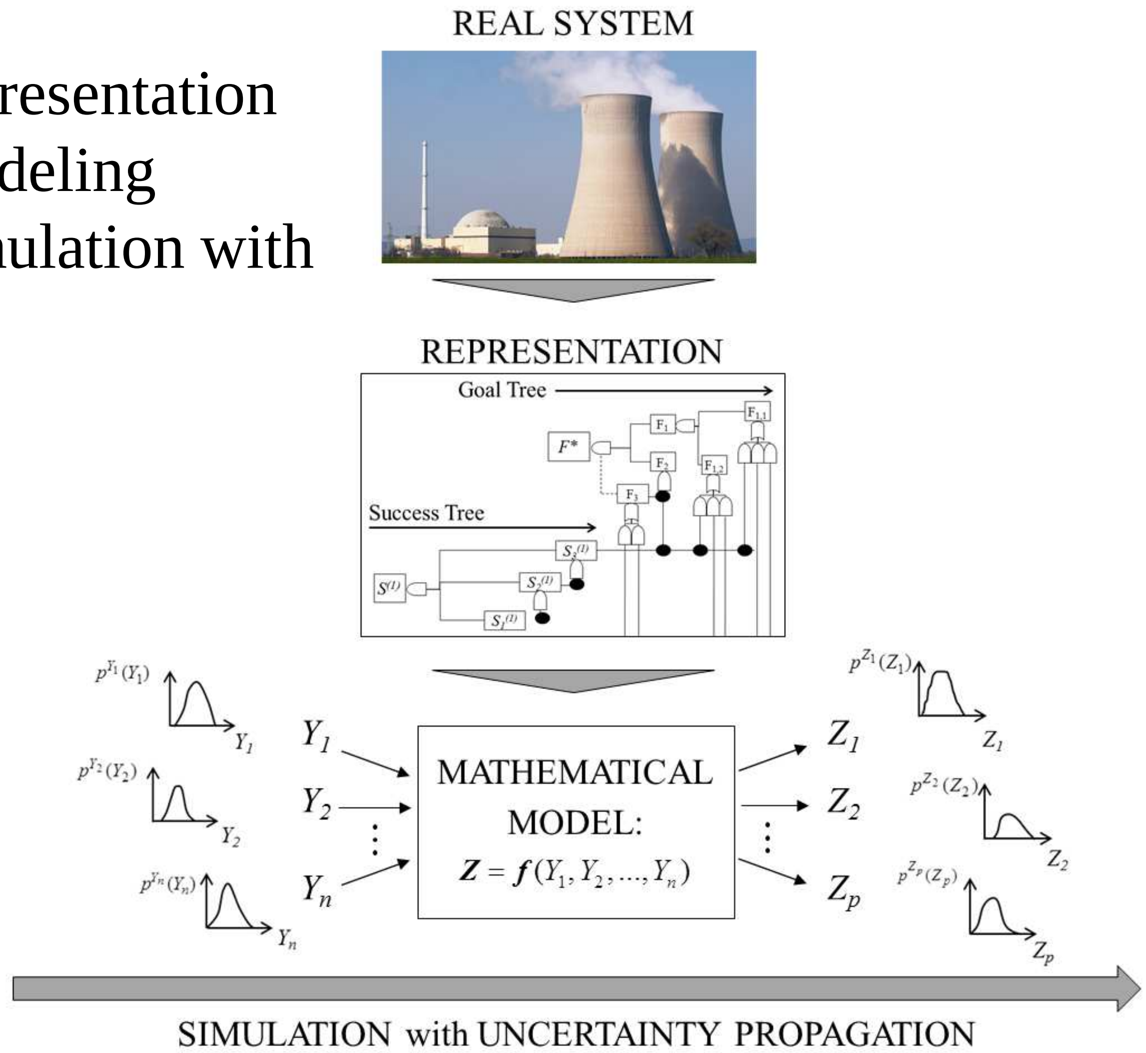
Systems (of systems) modeling: The issues

1) System(-of-systems) representation
2) System(-of-systems) modeling
3) System-(of-systems) simulation with uncertainty propagation

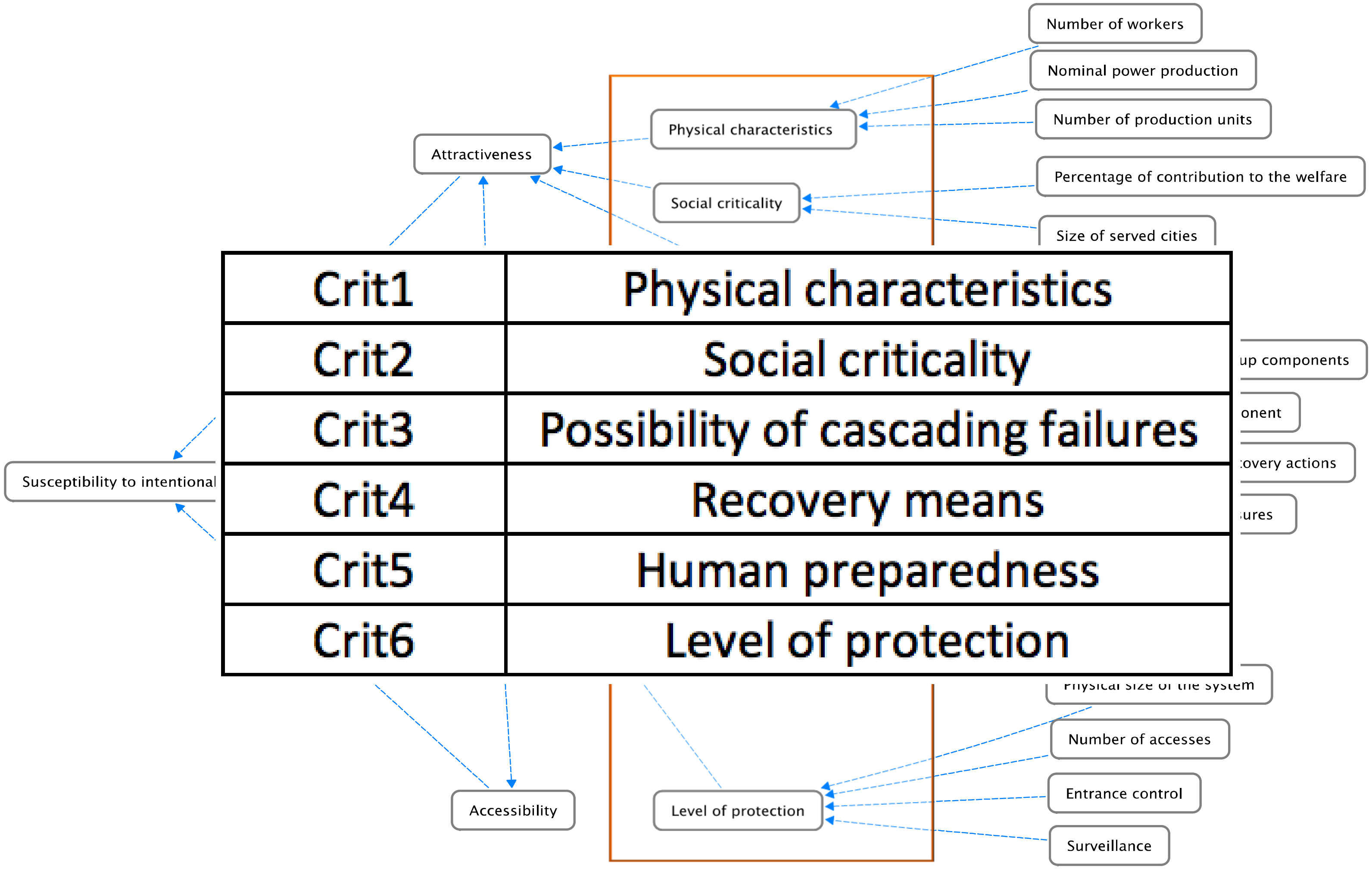
Uncertainty:

- Aleatory
- Epistemic



CI Vulnerability Assessment

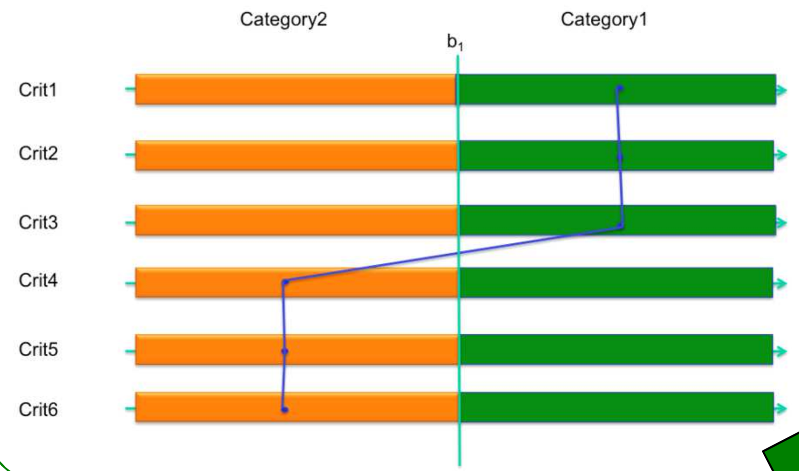
System susceptibility to intentional hazards: Criteria identification by hierarchical modeling



Crit1	Physical characteristics
Crit2	Social criticality
Crit3	Possibility of cascading failures
Crit4	Recovery means
Crit5	Human preparedness
Crit6	Level of protection

Sorting / Classification model

- System S_1
- System S_2
- …
- System S_9



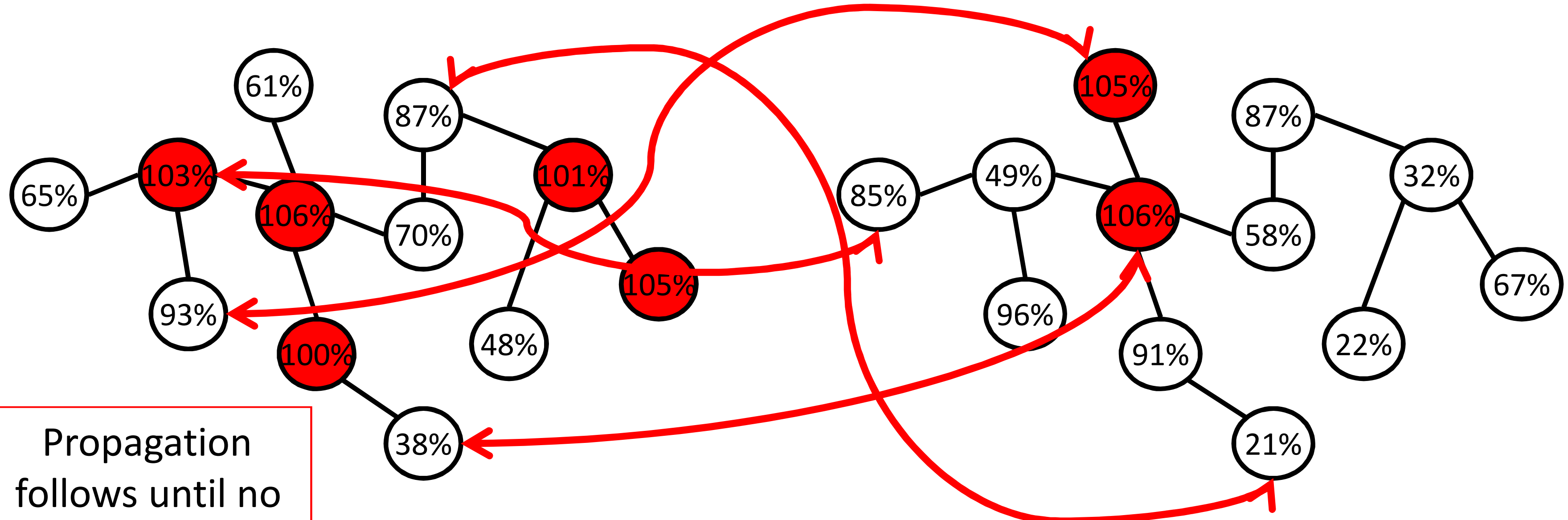
No.	Assignment
S1	2
S2	3
S3	3
S4	4
S5	3
S6	2
S7	3
S8	3
S9	2

Category	
1	Satisfactory
2	Acceptable
3	Problematic
4	Serious

CI Cascading Failures Modeling

Spreading rules:

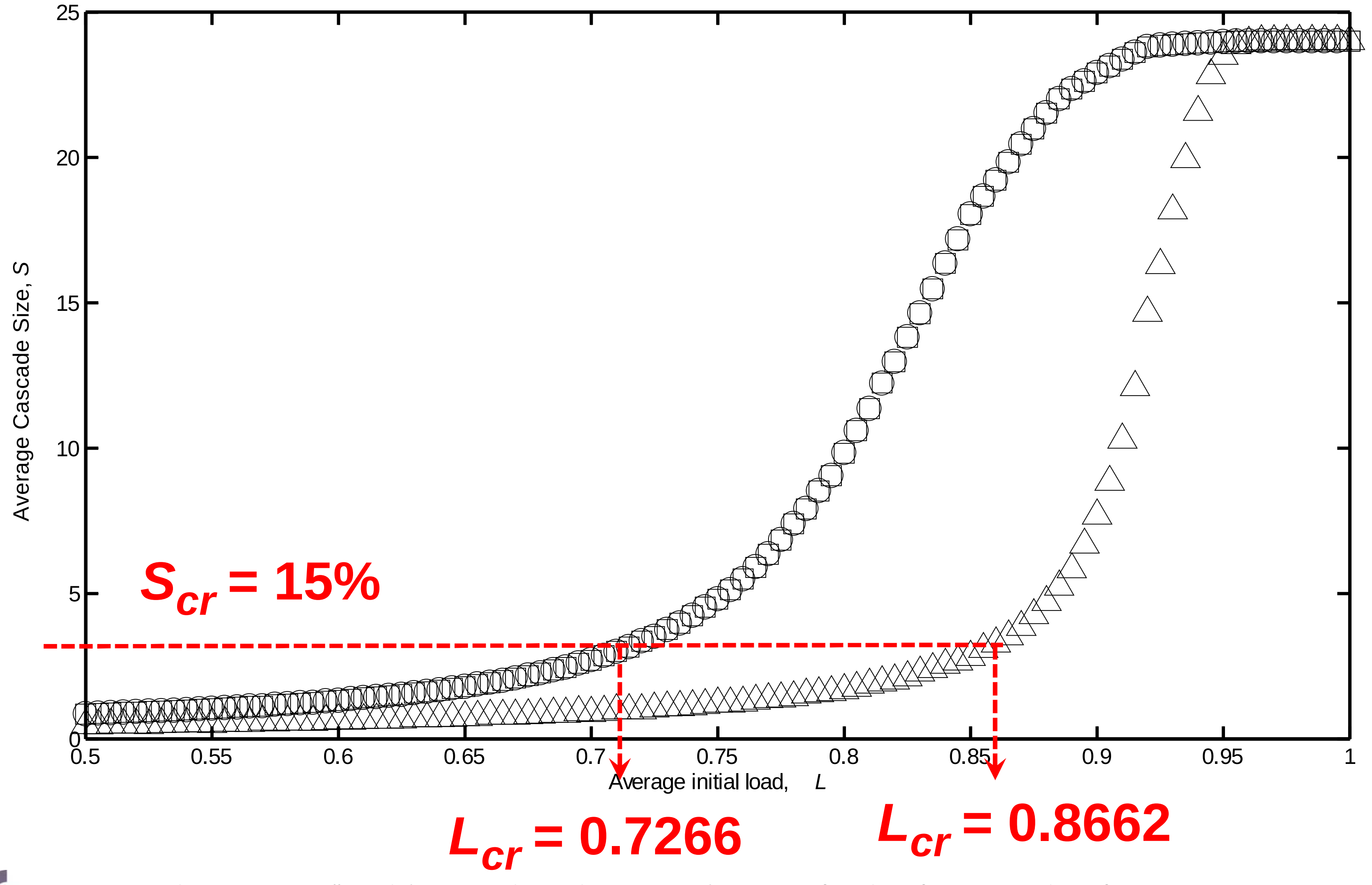
- fixed load (5%) transferred after a failure to neighboring nodes
- fixed load, *l*, (10%) transferred after a failure to interdependent nodes



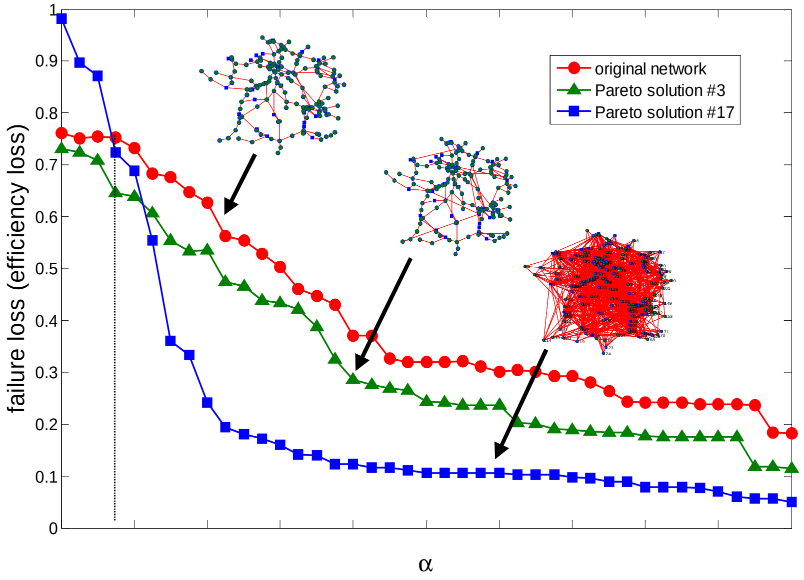
Propagation follows until no more working component can fail

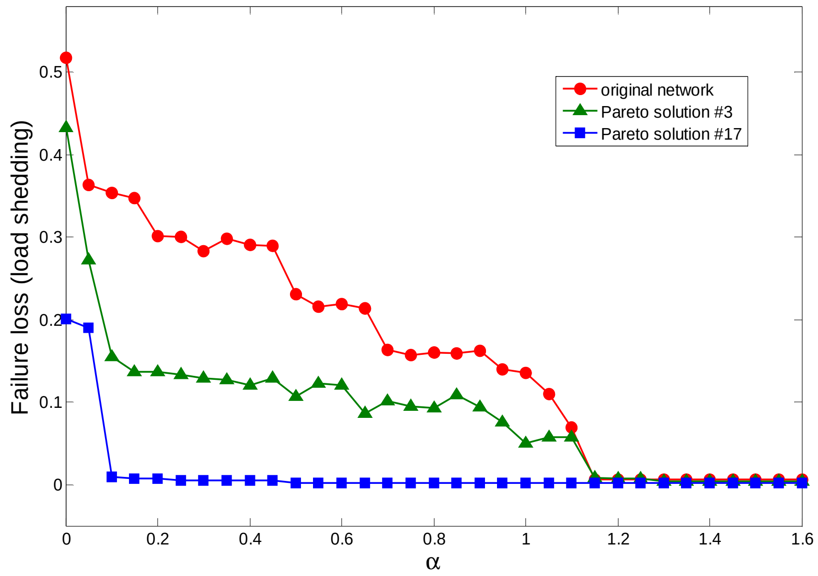
100% = component relative limit capacity

Initiating event: uniform disturbance (10%)



E. Zio and G. Sansavini, "*Modeling Interdependent Network Systems for Identifying Cascade-Safe Operating Margins*", IEEE Transactions on Reliability, 60(1), pp. 94-101, March 2011





Technical result: failure mitigation by adding redundant links at relatively light loading

Methodological/Conceptual result: results are consistent between the ML and OPA models: <u>topologically</u> robust network is <u>physically</u> robust

CI Resilience Assessment

Case study: Gas-Power interconnected infrastructures

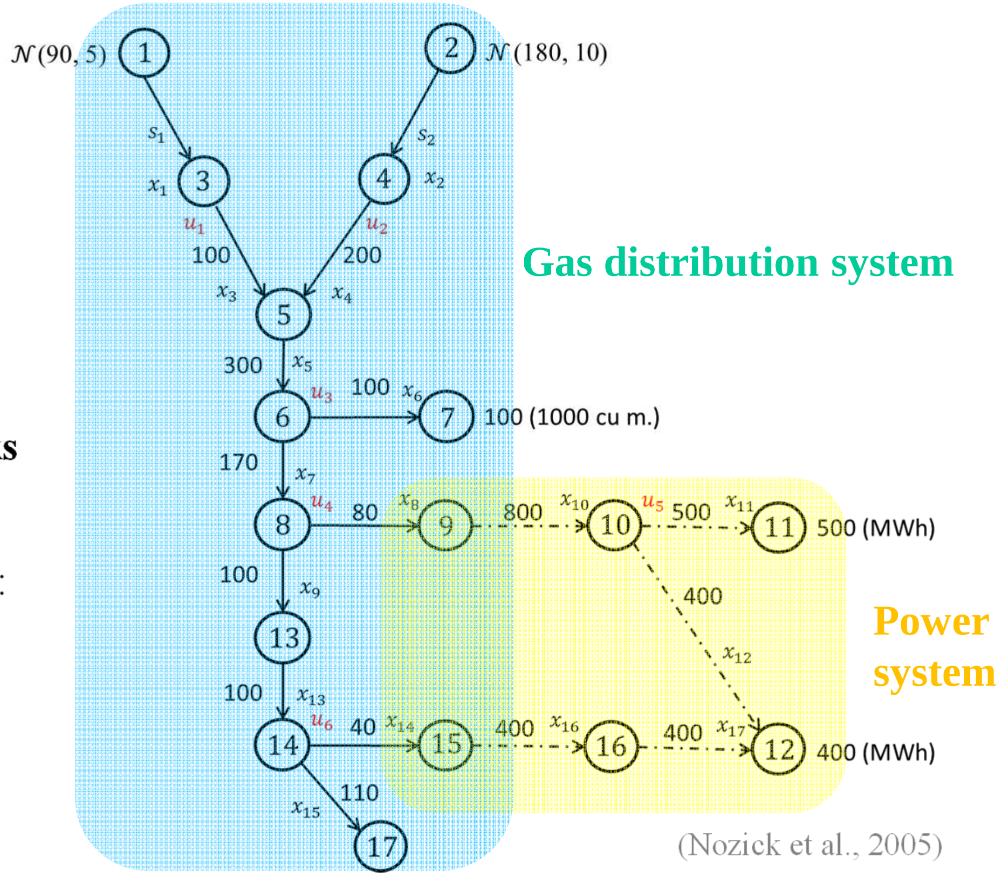
- With the **dynamics of system states**:
  (on the buffers and the links)

$$x^+ = Ax + Bu + s$$
$$y = Cx + Du$$

- Taking into consideration the **constraints/capacities of nodes and links**

- The **outputs of system** are states of users:

$$y = [x_6, x_{15}, x_{11}, x_{12}, x_{17}]$$
$$\rightarrow D_{D_1}, D_{D_2}, D_{L_1}, D_{L_2}$$



(Nozick et al., 2005)

- Solve the **optimization problem** in order to ensure the users demands:

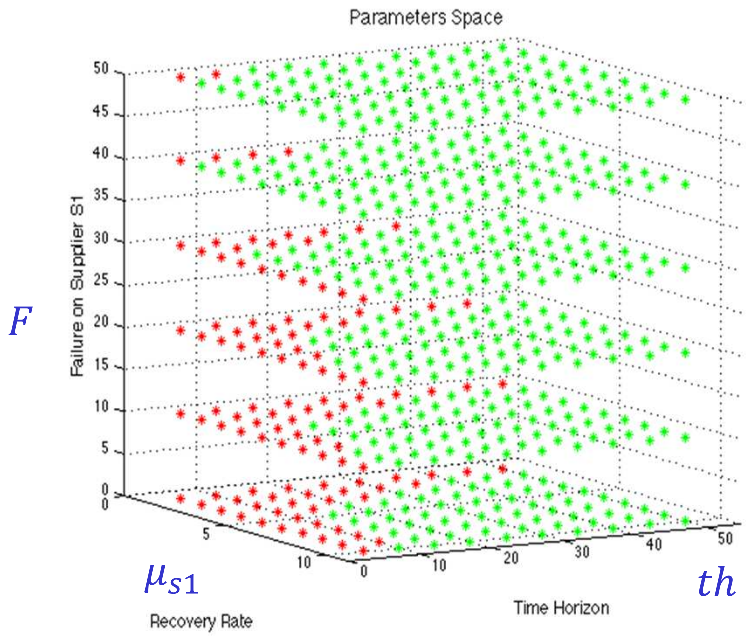
$$J = min(\omega_{D_1}|x_6 - D_{D_1}| + \omega_{D_2}|x_{15} - D_{D_2}| + \omega_{L_1}|x_{11} - D_{L_2}| + \omega_{L_2}|x_{12} + x_{17} - D_{L_2}|),$$

where $\omega_{D_1}, \omega_{D_2}, \omega_{L_1}, \omega_{L_2}$ are the weighting parameters of the users.

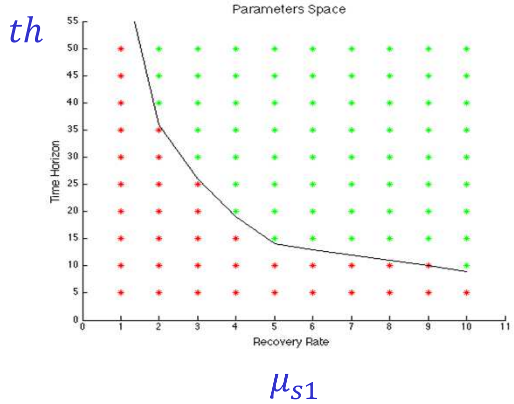
Case study: Gas-Power interconnected infrastructures

Resilience region

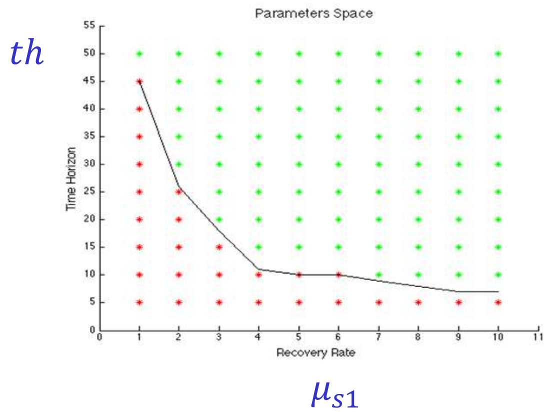
Parameter space $F \times \mu_{s1} \times th$



$F = 0$



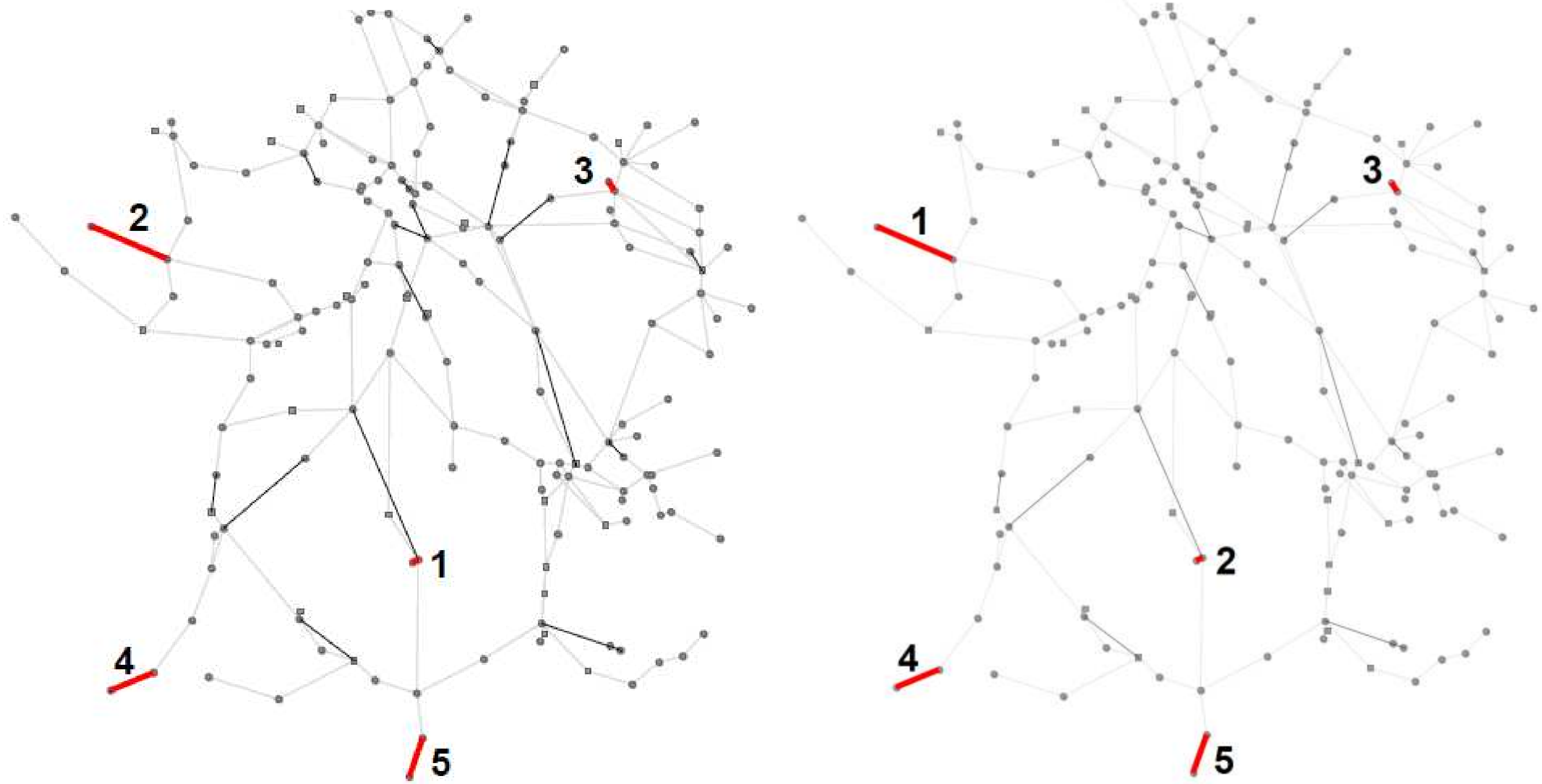
$F = 20$



*: Resilience region

*: Non-resilience region

(a) Scheduling *(b) MIP*



Technical result: similar restoration plans by heuristic scheduling algorithm & MIP

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Conclusions

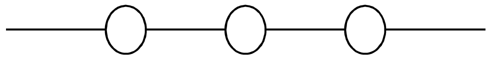
Structural complexity: heterogeneity, dimensionality, connectivity

Dynamic complexity : emergent behavior

Uncertainty: aleatory, epistemic, perfect storms, black swans

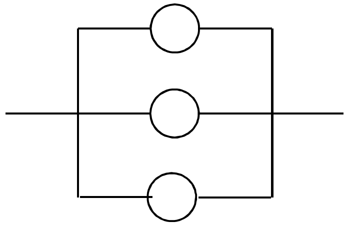
Complexity

Series



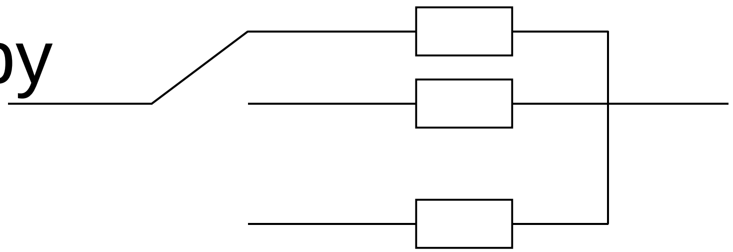
$$R(t) = \prod_{i=1}^{N} R_i(t)$$

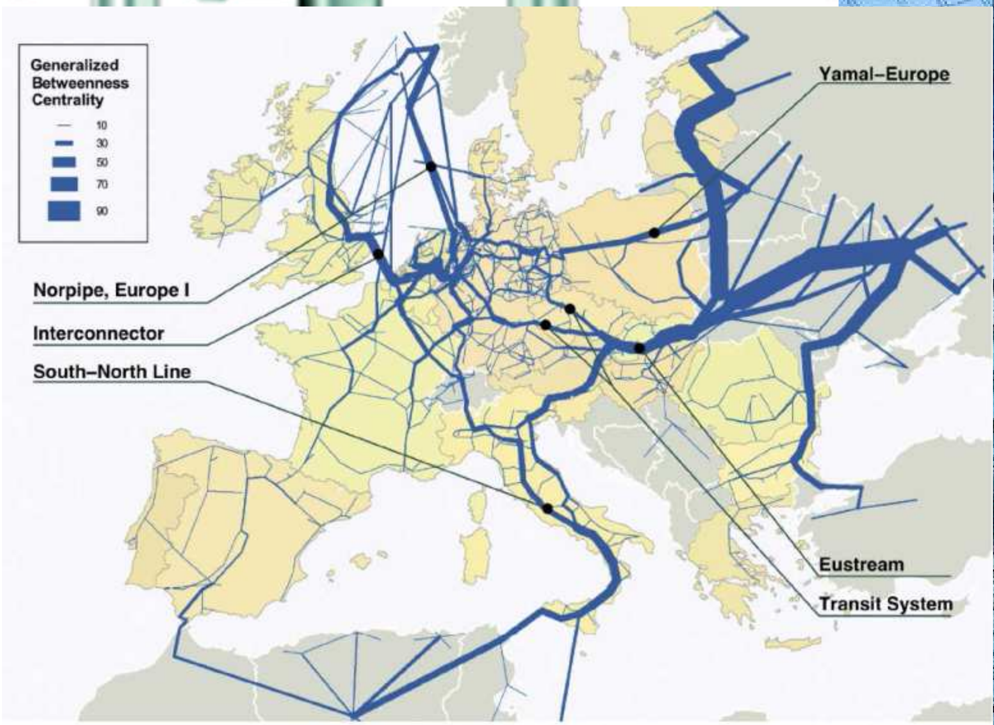
Parallel



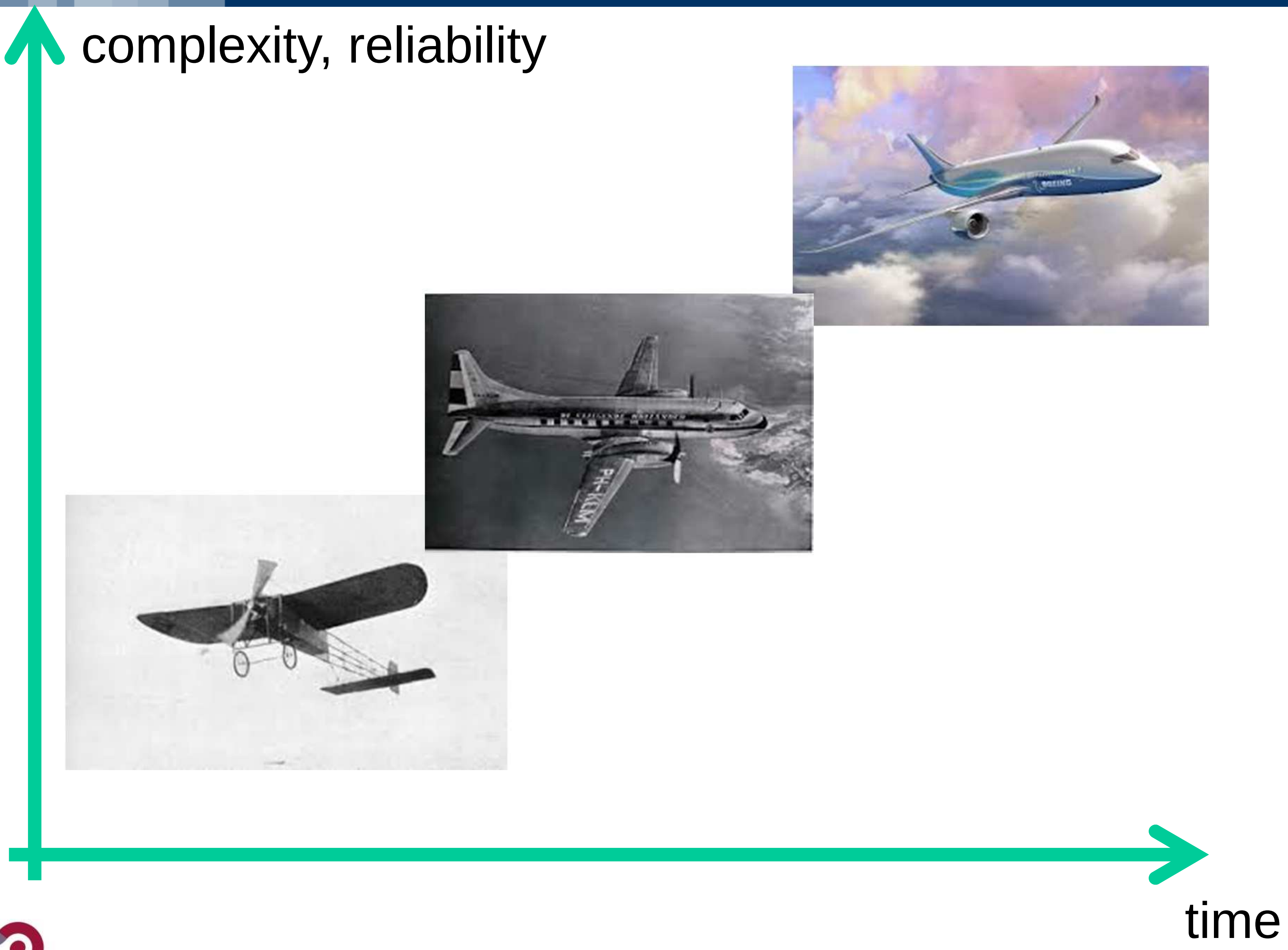
$$R(t) = 1 - \prod_{i=1}^{N} \left[1 - R_i(t)\right]$$

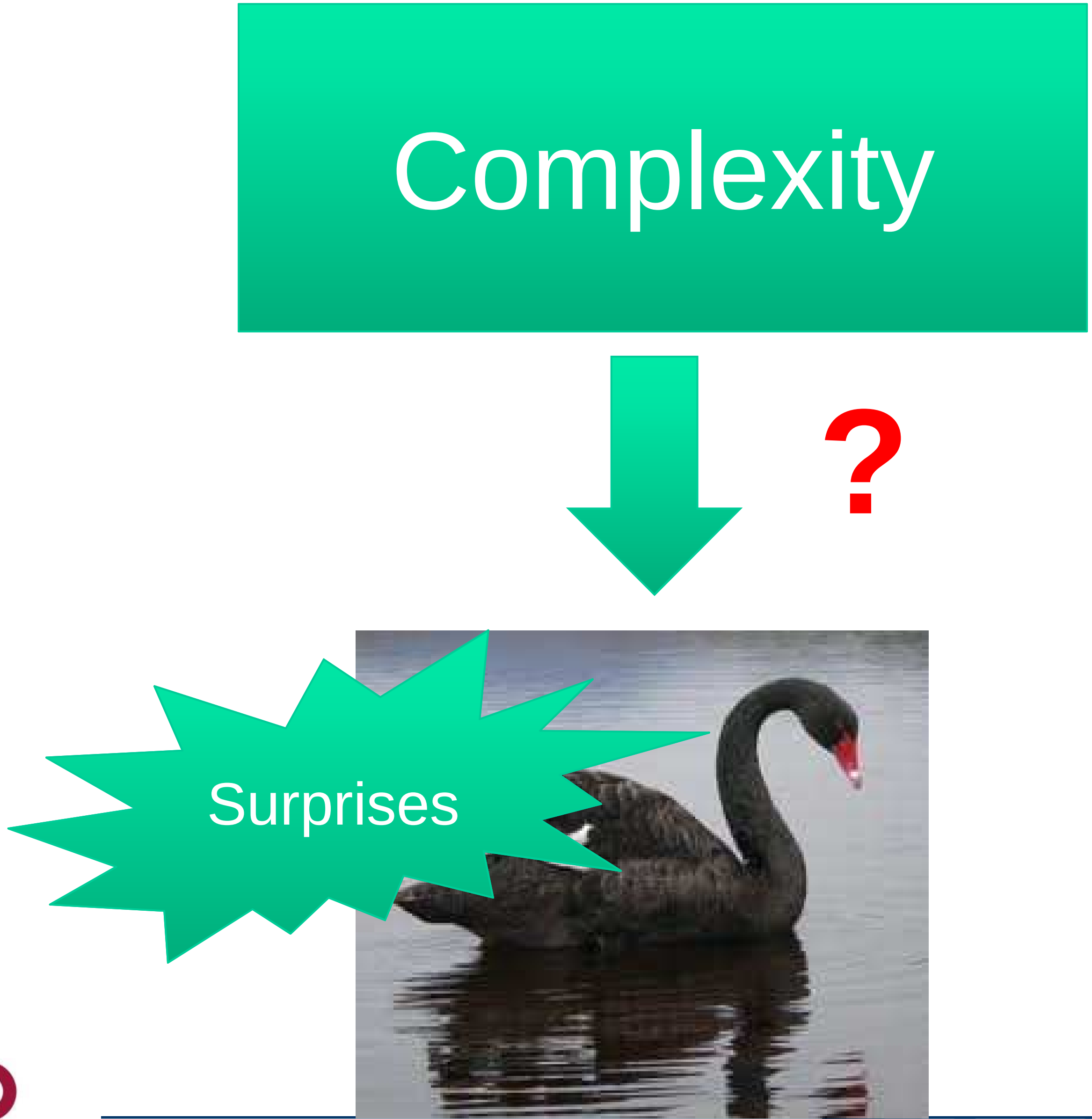
Standby




Generalized Betweenness Centrality
10
30
50
70
90
Yamal–Europe
Norpipe, Europe I
Interconnector
South–North Line
Eustream
Transit System

Complexity and reliability




Complexity
?
Surprises

System analysis:

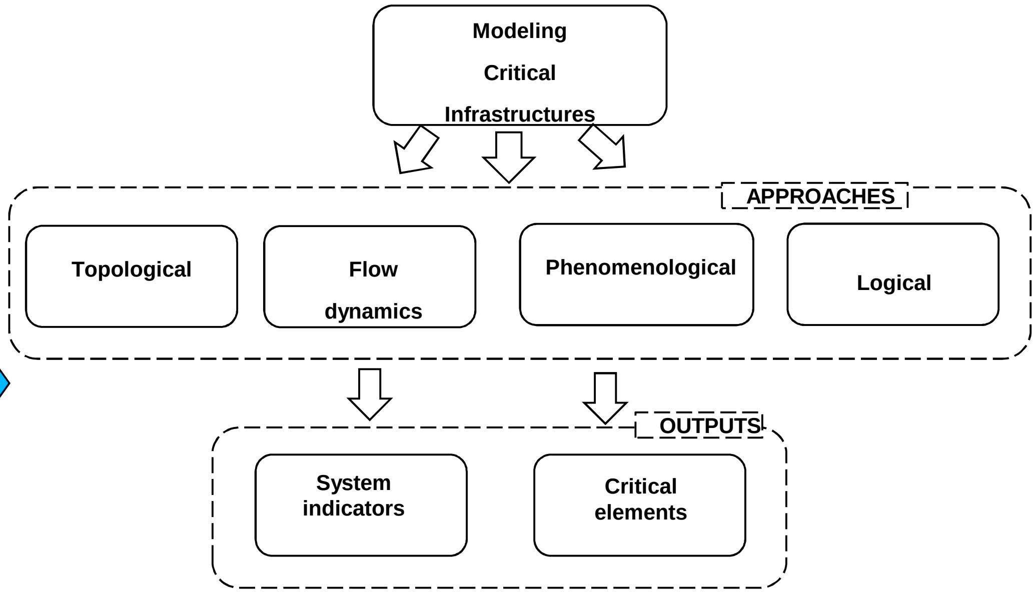
- hazards and threats identification
- physical and logical structure identification
- dependencies and interdependences identification and modeling
- failure/resilience dynamics analysis (cascades)

Quantification of system safety indicators

Identification of critical elements

Application for system improvements:

- design
- operation
- interdiction/protection

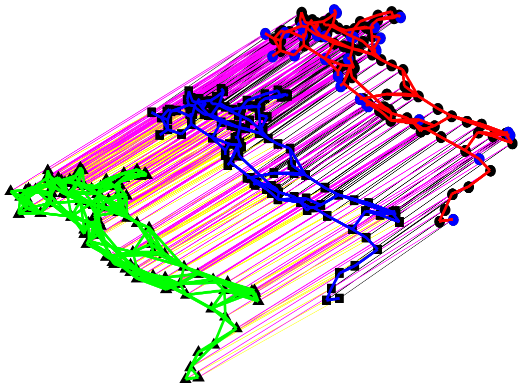


Systems of systems

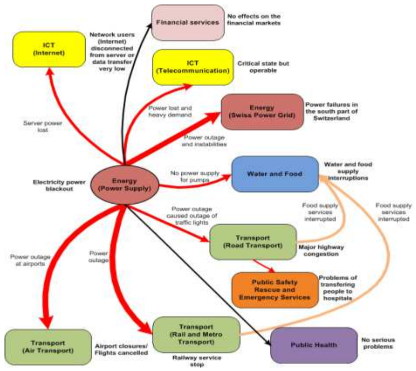
W. Kroger and E. Zio, *"Vulnerable Systems"*, Springer, 2011

Conclusions: Modeling for critical infrastructures protection and resilience

Object



Analysis



Why

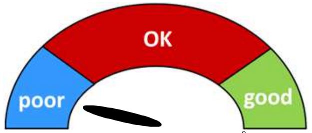
1. System(-of-systems) representation
2. System(-of-systems) modeling
3. System(-of-systems) behavior quantification (by simulation) accounting for the presence of uncertainty (aleatory and epistemic)

Structural Complexity + Dynamic Complexity

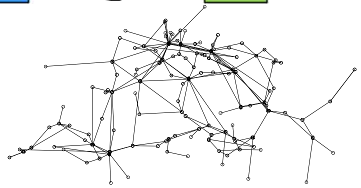
Modeling, Simulation, Optimization and Computational Challenges

Topological

Detail



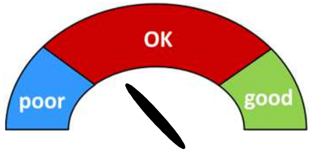
Computational cost



Phenomenological

$$\begin{cases} \dot{x}_i = -\mu_i\left(x_i - \sum_{i\in I_i}\alpha_{ji}x_j\right) + w_i; & if\ x_i \le \sigma_i, i,j \in 1,\dots,N_s;\ i \ne j, \\ \dot{x}_i = \lambda_i(1-x_i)\ ; & if\ x_i > \sigma_i, i,j \in 1,\dots,N_s;\ i \ne j, \end{cases}$$

Detail

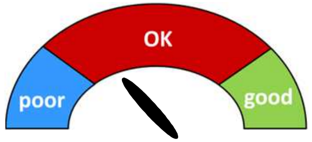


Computational cost

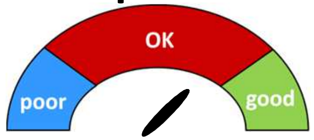
Uncertainty

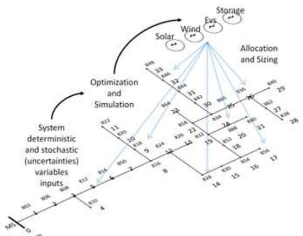
Logic

Detail



Computational cost

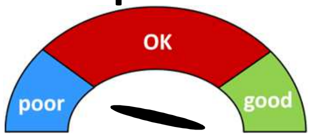




Flow dynamics

Detail

Computational cost



Integrated Approach