CentraleSupélec

Fondation CentraleSupélec

Chair Risk and Resilience of Complex Systems

http://rrcs.centralesupelec.fr/en

Annual Scientific Seminar
November 17th 2022

Introduction

Anne Barros – Head of the chair

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- 3 permanent members: Anne Barros, Yiping Fang, Zhiguo Zeng
- 1 associate member: David Coit – Rutgers University - USA
- 2 PHD students: Andrea Bellè, Matthieu Roux

- CentraleSupélec students
- Master students

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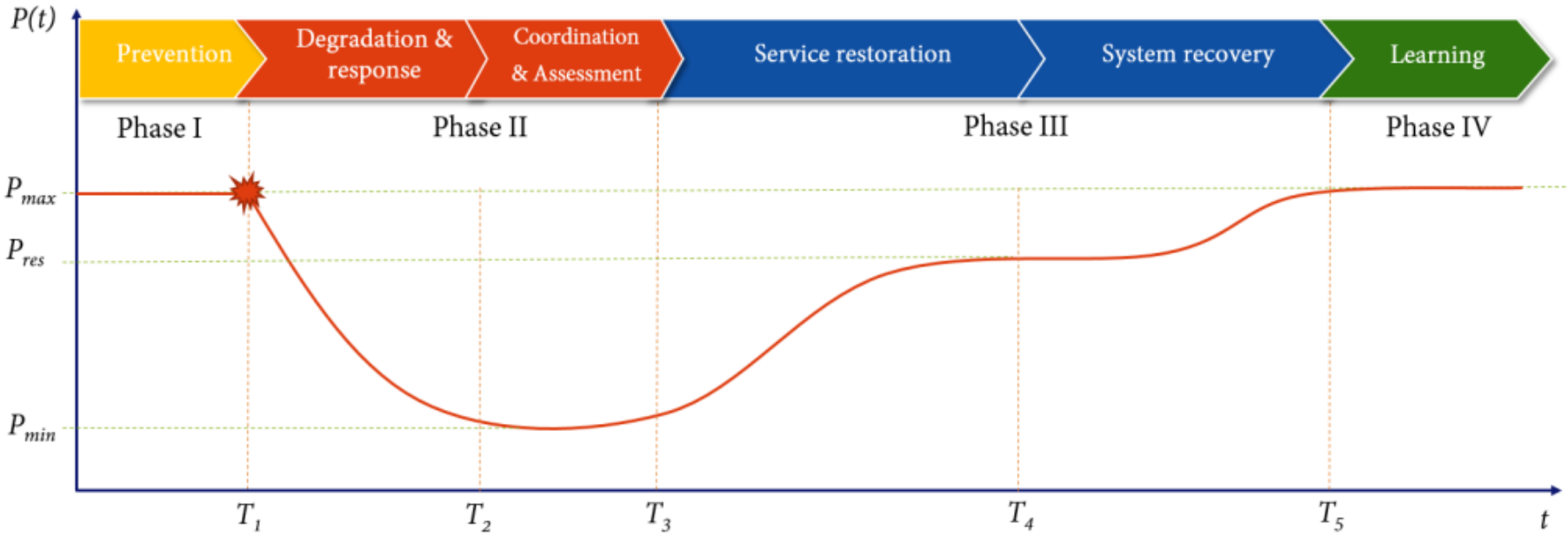
Agenda

- PHD project presentations
- Methodological perspectives
- Towards future collaborations and next steps for addressing new challenges
  - Round Table - The floor is yours
  - Proposals for futur research projects (Anne Barros)
  - Complements from the COPIL
  - Discussion

Scientific project

- Axis 1: Modelling of systems of systems and their interdependences for risk management and resilience between several operators
- Axis 2: Modelling and optimisation of maintenance tasks in order to reduce their impact on service continuity (internally and between operators)
- Axis 3: Common models and methods platform

Resilience perspective



energies

Review paper

Resilience Quantification of Smart Distribution Networks – A Bird's Eye View Perspective

Youba Nait Belaid[1,2]; Patrick Coudray[1]; José Sanchez-Torres[1]; Yi-Ping Fang[2,*]; Zhiguo Zeng[2]; Anne Barros[2]

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Competences

- Risk analysis, reliability, prognosis, maintenance
- Probabilistic and stochastic modeling
- Data analysis
- Mathematical programming
- Stochastic optimization
- Decision making under uncertainty
- Integration of AI techniques
- Integration of the human factor

Axis 1

Modelling of systems of systems and their interdependences for risk management and resilience between several operators

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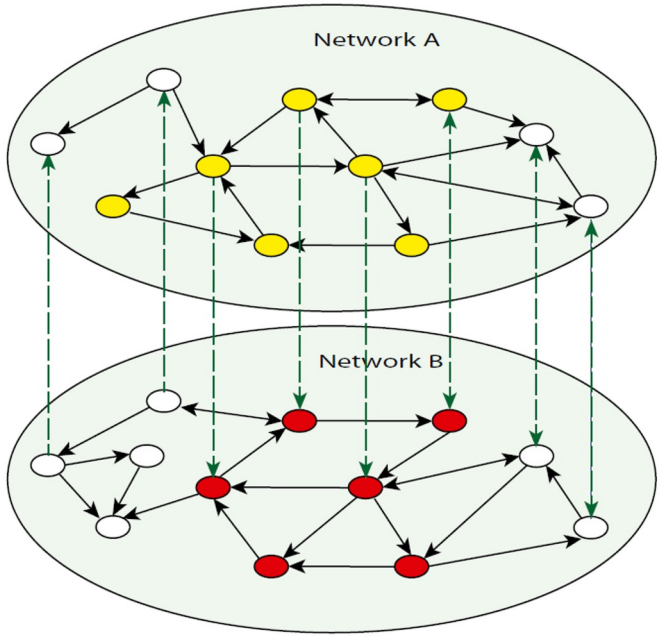
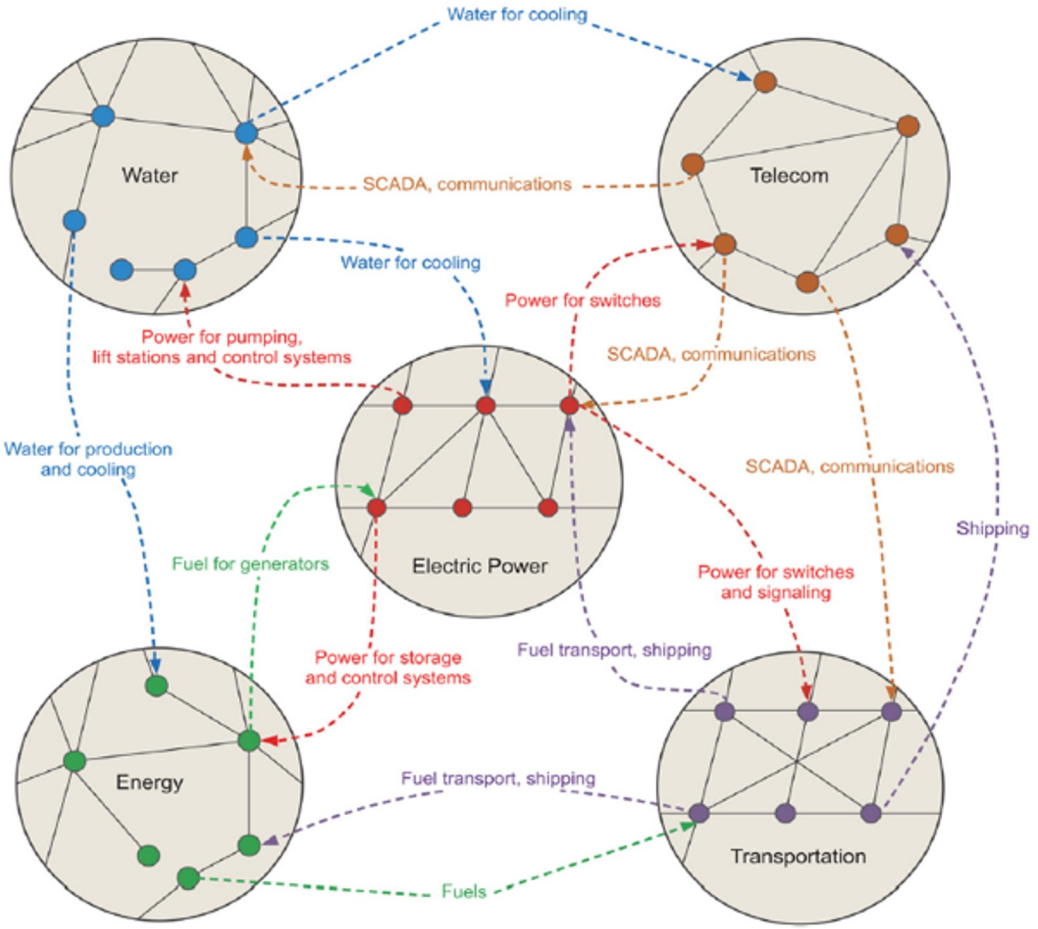
Modelling interdependent networks
Andrea Bellè (Chaire RRSC)





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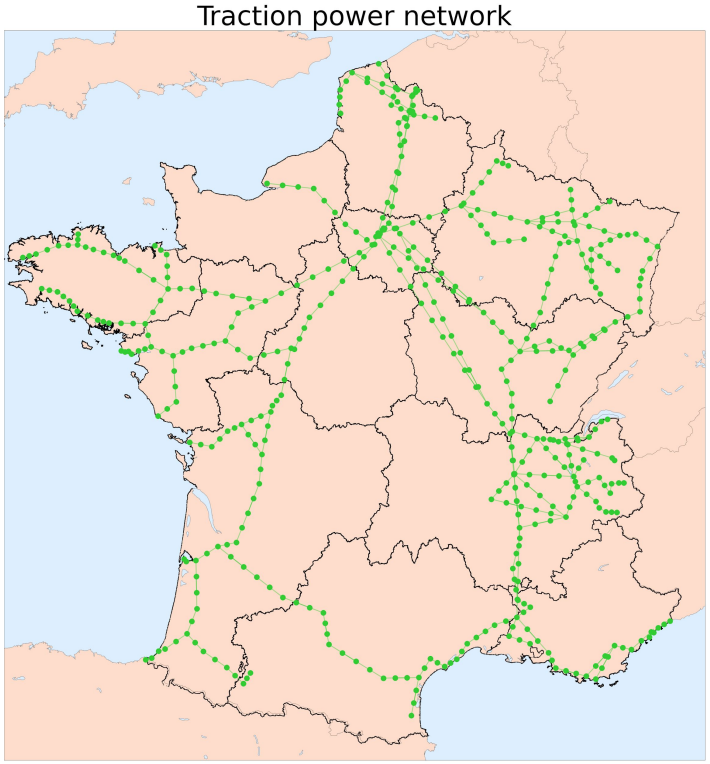
Vulnerability analysis

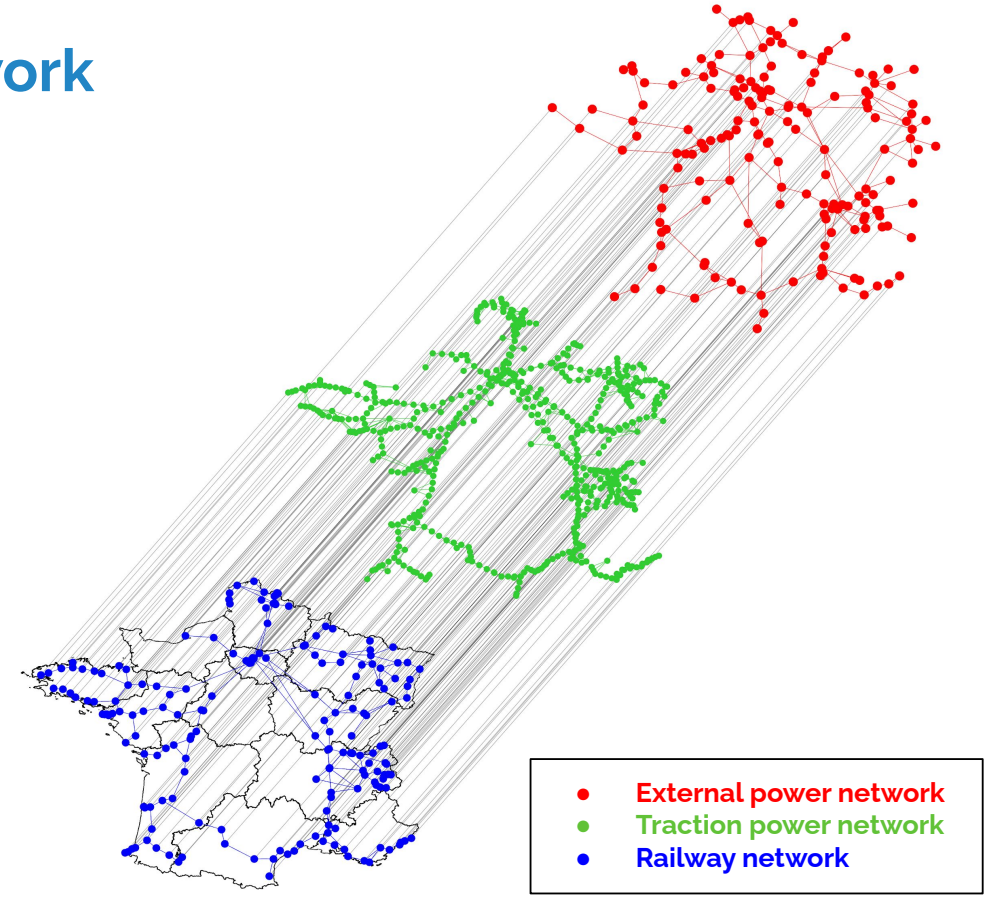
Systematically and comprehensively identifying the possible states a system can be put into, due to specific strains, and estimating the negative consequences associated with them.

Quote from: Johansson, Jonas, Henrik Hassel, and Alexander Cedergren. "Vulnerability analysis of interdependent critical infrastructures: case study of the Swedish railway system." *International journal of critical infrastructures* 7, no. 4 (2011): 289-316.

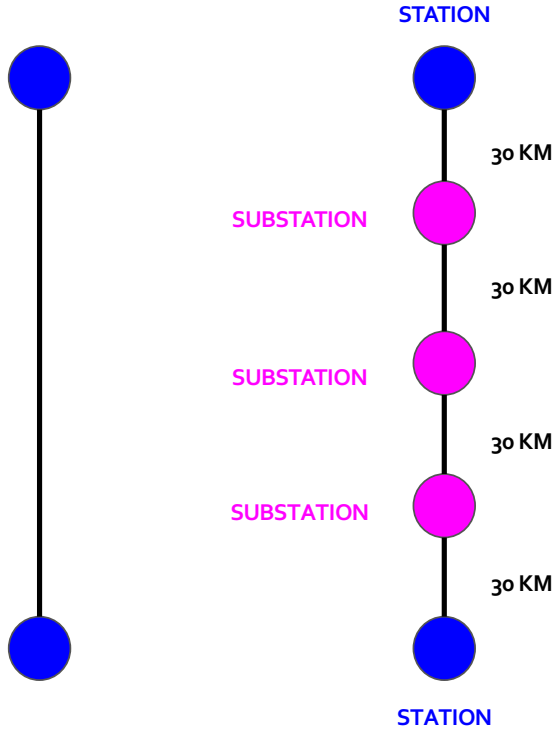
Coupling interface modeling

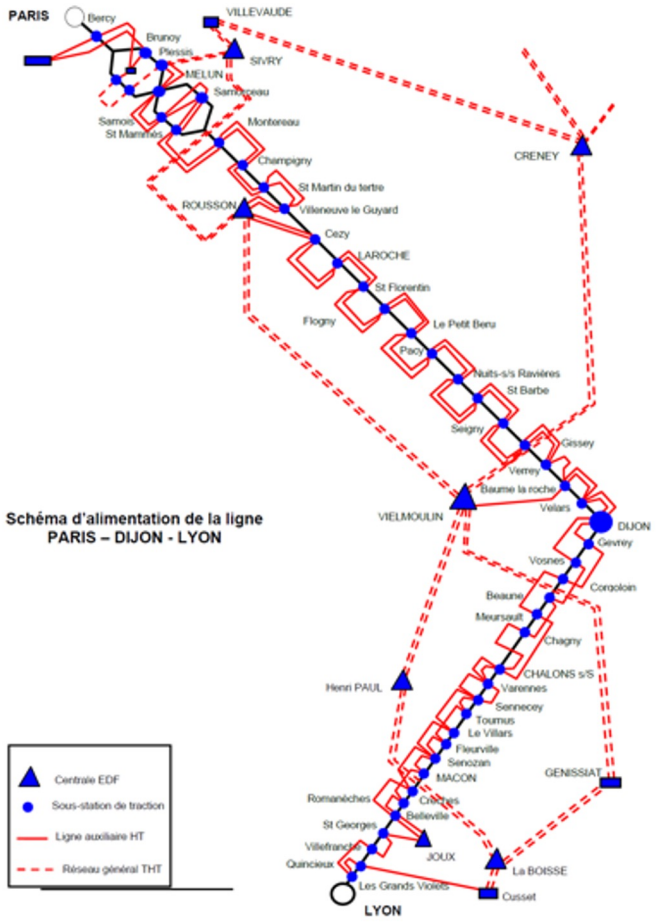
Traction power network





Coupling interface modeling





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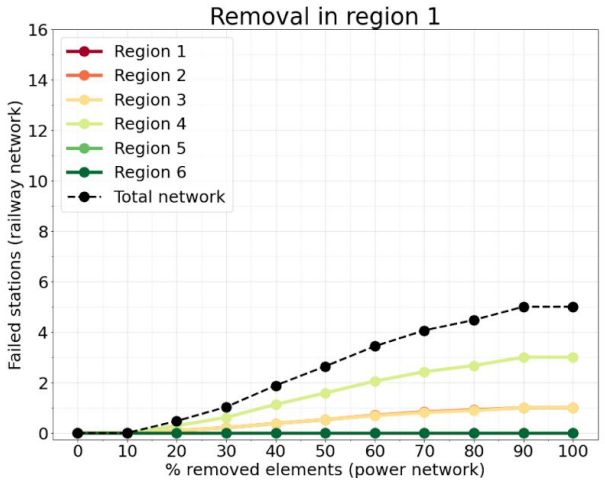
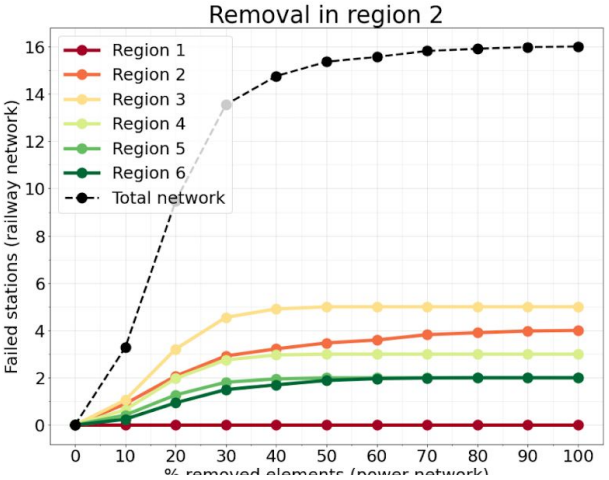
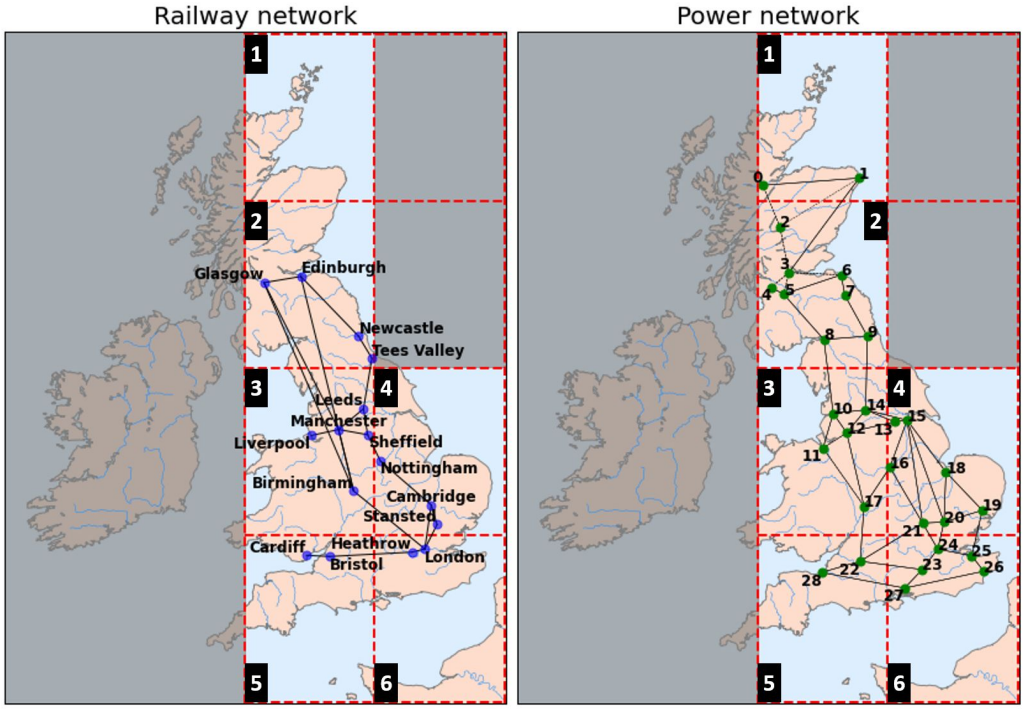
Spatial scale







Region	Generation [MW]	Load_{tot} [MW]	$\text{Load}_{\text{rail}}$ [MW]
1	2174.96	981	0.0
2	8942.97	7094.5	4371.0
3	14525.73	15068.0	11708.0
4	14008.20	10087.36	3614.0
5	7977.33	7311.0	7311.0
6	9662.03	15784.0	9734.0

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Optimising coupling interface

?

How to design the coupling interface between interdependent critical infrastructures?

Existing literature

Most of the times the coupling interface is a given parameter

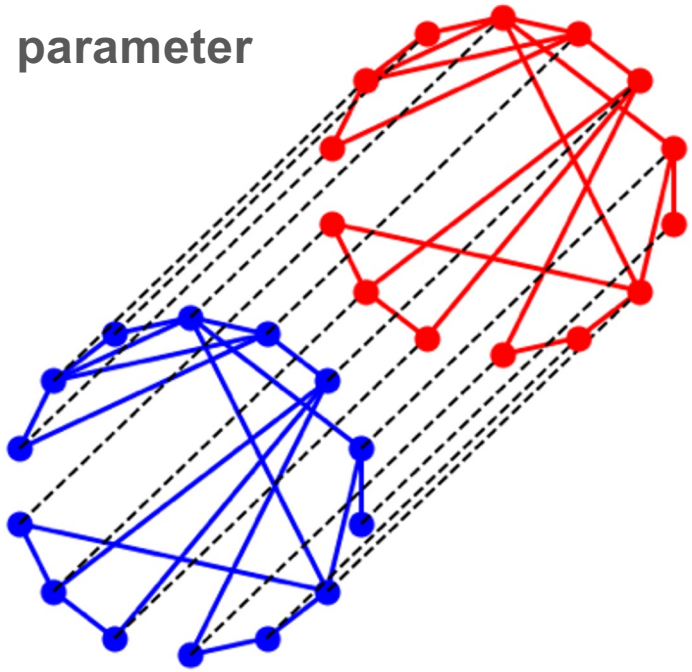
- Different interface designs not considered

Network metrics-based coupling (e.g. [1]-[2])

- Degree, betweenness
- At best an "educated guess"

Network metrics-based heuristics (e.g. [3]-[4])

- Global optimum not guaranteed



[1] Rueda, Diego F., and Eusebi Calle. "Using interdependency matrices to mitigate targeted attacks on interdependent networks: A case study involving a power grid and backbone telecommunications networks." *International Journal of Critical Infrastructure Protection* 16 (2017): 3-12.

[2] Guo, Hengdao, Samson S. Yu, Herbert HC Iu, Tyrone Fernando, and Ciyan Zheng. "A complex network theory analytical approach to power system cascading failure—From a cyber-physical perspective." *Chaos: An Interdisciplinary Journal of Nonlinear Science* 29, no. 5 (2019): 053111.

[3] Ouyang, Min, and Leonardo Dueñas-Osorio. "An approach to design interface topologies across interdependent urban infrastructure systems." *Reliability Engineering & System Safety* 96, no. 11 (2011): 1462-1473.

[4] Winkler, James, Leonardo Dueñas-Osorio, Robert Stein, and Devika Subramanian. "Interface network models for complex urban infrastructure systems." *Journal of Infrastructure Systems* 17, no. 4 (2011): 138-150.

Power and gas network (IPGN)

POWER NETWORK

- 14 nodes
- 20 edges

GAS NETWORK

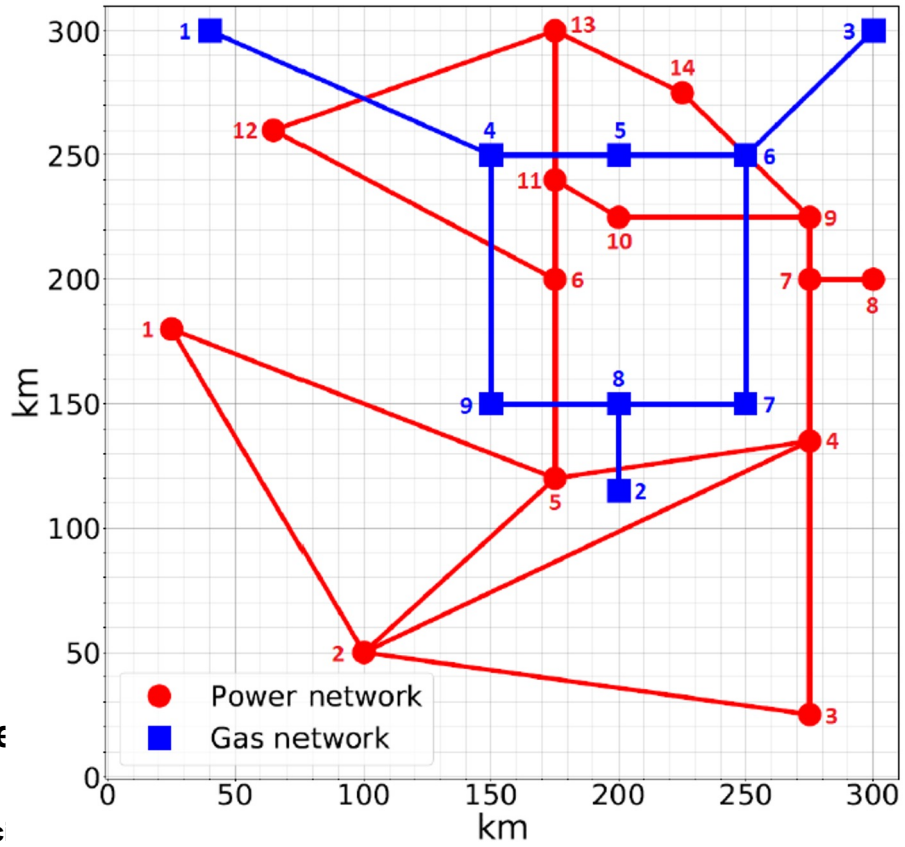
- 9 nodes
- 9 edges

FAILURE SCENARIOS

- Number of elements failed bounded by K_{att}

COUPLING INTERFACE - INTERDEPENDENCIES

- Each node in GN dependent on 1 node in PN
- Each generator in PN dependent on 1 node in GN
- Each interdependency has a cost per kilomete
- The total cost of the coupling interface is bounded by the available monetary budget B_c



Optimal coupling interface

$$\max_{\substack{\{\mathbf{p}^0,\mathbf{d}^0,\mathbf{f}^0,\boldsymbol{\theta}^0,\boldsymbol{\delta}^0\}\\ \mathbf{y}\in\mathcal{C}}} \min_{\mathbf{u}\in\mathcal{A}} \max_{\{\mathbf{p},\mathbf{d},\mathbf{f},\boldsymbol{\theta},\boldsymbol{\delta}\}} w_{PN}\frac{\sum_{i\in V_{PN}} d_i}{\overline{d}_{PN}^{max}} + w_{GN}\frac{\sum_{i\in V_{GN}} d_i}{\overline{d}_{GN}^{max}}$$

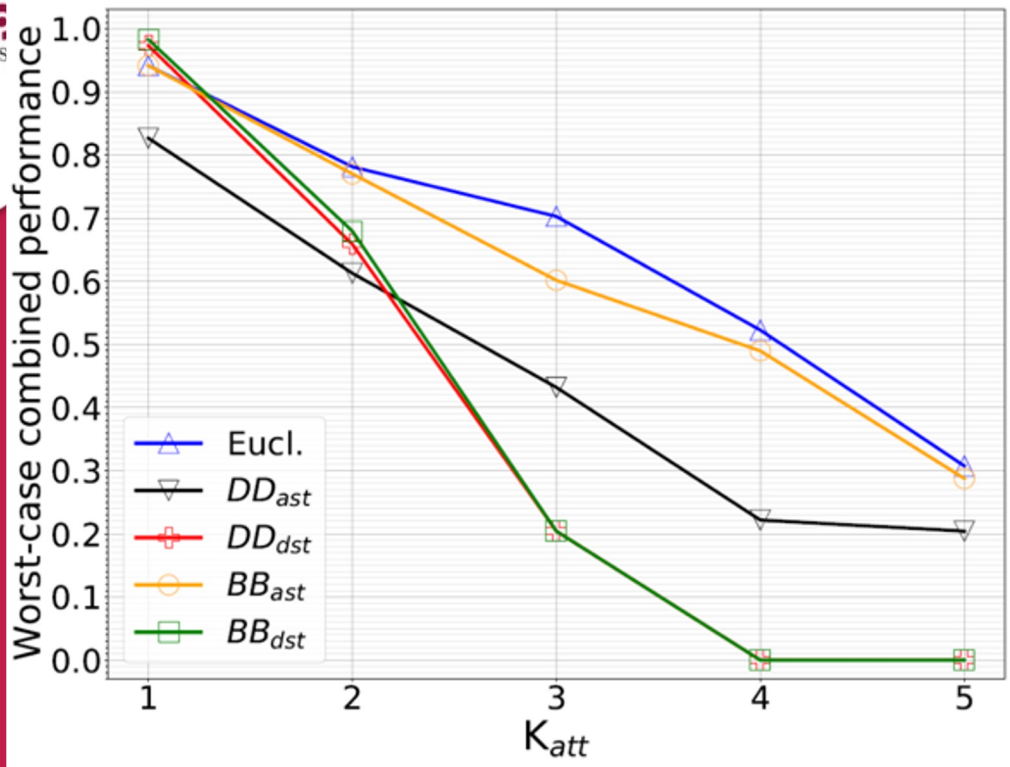
- Tri-level optimization model
- Combined performance of interdependent CIs
- Identification of the most robust coupling interface (maximization of performance in the worst-case failure scenario)

Defender-Attacker-Defender

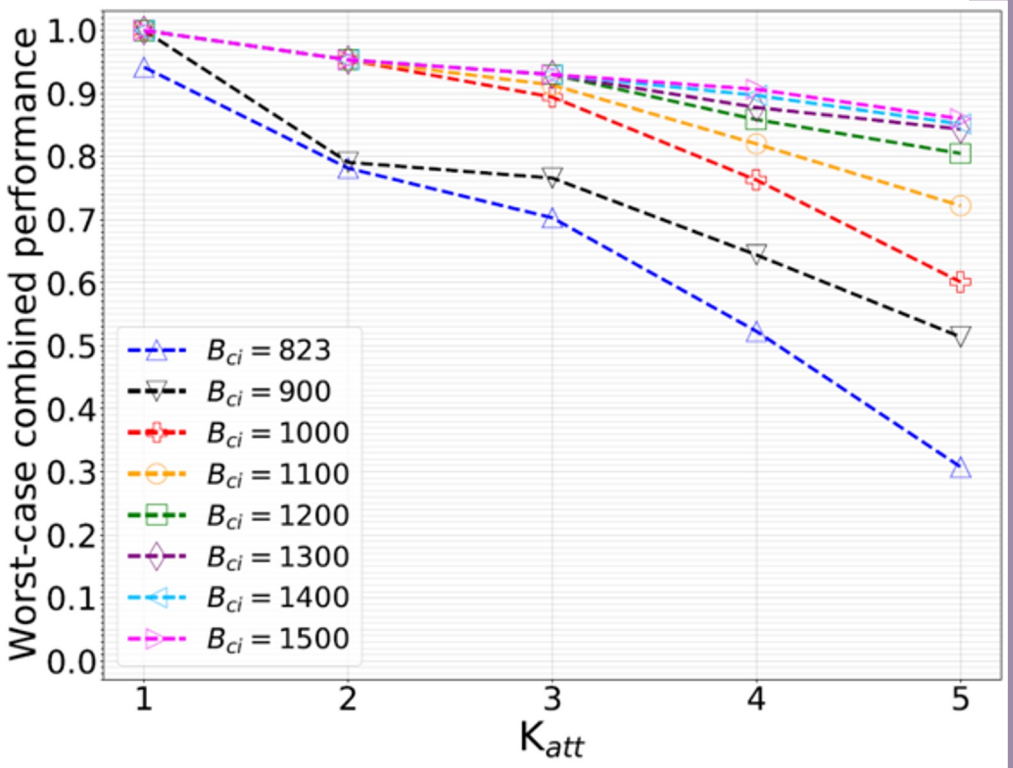
$$\max_{\substack{\{\mathbf{p^0},\mathbf{d^0},\mathbf{f^0},\boldsymbol{\theta^0},\boldsymbol{\delta^0}\}\\ \mathbf{y}\in\mathcal{C}}} \min_{\mathbf{u}\in\mathcal{A}} \max_{\{\mathbf{p},\mathbf{d},\mathbf{f},\boldsymbol{\theta},\boldsymbol{\delta}\}} w_{PN}\frac{\sum_{i\in V_{PN}} d_i}{\overline{d}_{PN}^{max}} + w_{GN}\frac{\sum_{i\in V_{GN}} d_i}{\overline{d}_{GN}^{max}}$$

- **DEFENDER (OPERATIONS)**: optimize operational variables (power/gas production, supply, flow, etc.) in order to maximize the combined performance
- **ATTACKER (LINES)**: choose a feasible attack plan in order to minimize the combined performance (in other words, find the worst-case attack plan)
- **DEFENDER (PLANNER)**: optimize coupling variables (interdependencies) in order to maximize the combined performance under the worst-case attack

Some results



(a) Network-based coupling interfaces



(b) Optimal coupling interfaces

Bellè Andrea, Abdin F. Adam, Zeng Zhiguo, Fang Yi-Ping and Barros Anne, "A mathematical framework for the optimal coupling of interdependent critical infrastructures", *IEEE Transactions on Systems, Man and Cybernetics: Systems, under review*

Associated projects

- APP ANR JCJC – CE39 – Sécurité globale, Résilience et gestion de crise, Cybersécurité . Yiping Fang is leading a 4 years project: “Robust and Scalable Prescriptive Analytics for the Resilience of Critical Infrastructure Networks”

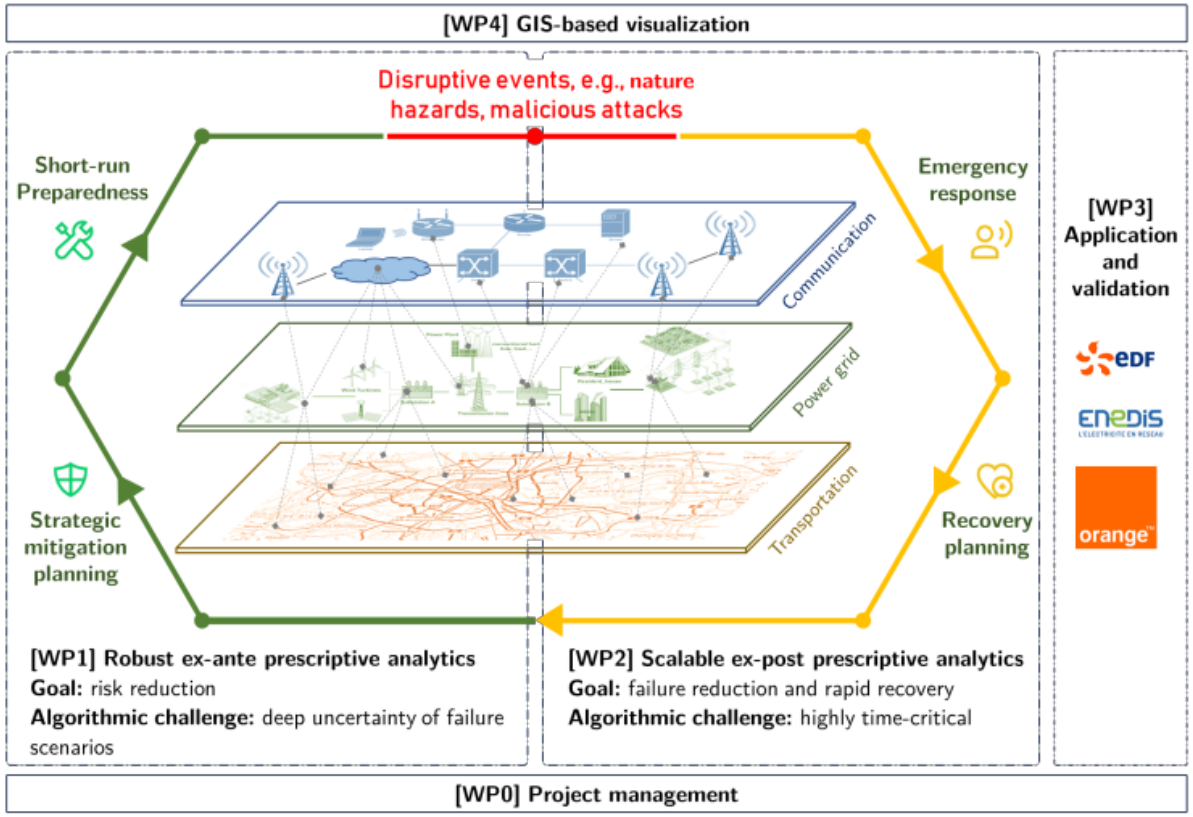


Fig. 1. The overall structure of the project

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Axis 2

Modelling and optimisation of maintenance tasks in order to reduce their impact on service continuity (internally and between operators)

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Maintenance optimization planification critical infrastructures
Matthieu Roux (Chaire RRSC)

Fleets are complex distributed systems to maintain

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Objective: optimize **condition-based maintenance (CBM)** strategies

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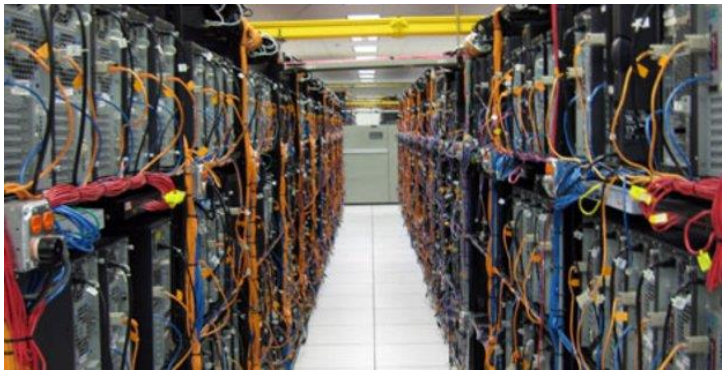

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Layout

The study is decomposed into 2 steps

- **Step 1: Optimize a CBM policy on a 1-item system**
  - Fix the degradation model
  - Model the monitoring quality
  - Compare solving algorithms

- **Step 2: Generalize to large distributed systems**
  - System level constraints (ressource, availability, etc…)
  - Opportunistic maintenance considerations
  - ⚠ Curse of dimensionality ⇾ heuristic or hybrid approaches

Associated projects

- APP ANR JCJC – H19 – Industrie du Futur : homme, organisation, technologies. Zhiguo Zeng is leading a 4 years project: “Digital Failure Twin for online reliability assessment and predictive maintenance of future manufacturing systems”

Challenges to the reliability of future industrial systems:

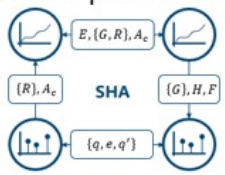
- Few failure data available. ⇨ New reliability model needed.
- Existing digital twin-based models only consider a single failure process. ⇨ Need to consider multiple dependent failure processes.

In this project, we intend to develop:

- Digital Failure Twin (DFT).
- Online reliability assessment methods based on DFT.
- Predictive maintenance models based on DFT.

Digital twin

Multiple dependent failure processes

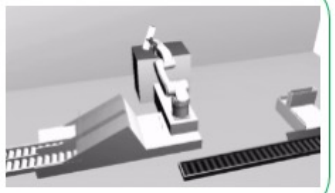


In order to:

- Improve the reliability.
- Reduce the operation costs of future manufacturing systems.

Use cases:

- An intelligent production line
- Supported by GE Healthcare



Associated projects for Axis 1 and 2

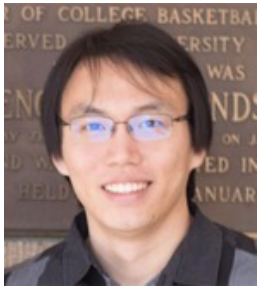
- Master projects
  - Building a (deep) reinforcement learning model for the optimization of condition-based maintenance planning with imperfect monitoring
  - Resilience and optimization of power systems with high penetration of renewables considering climate change
- Second year projects
  - Evaluation and improvement of a deep reinforcement learning model for the planning of condition-based maintenance operations in a large-scale industrial system
  - Recommissioning Networked-Systems During Extreme Events Using Machine Learning
- Internships

Visiting Professors

- David Coit
  - Department of Industrial System Engineering
  - Rutgers University
  - https://www.davidcoit.net/home

- John Andrews
  - Resilience Engineering Research Group
  - Nottingham University - Llyod's Register Foundation
  - https://www.nottingham.ac.uk/engineering/people/john.andrews

- Hiba Baroud
  - Associate Chair, Civil and Environmental Engineering
  - Vanderbilt University
  - https://engineering.vanderbilt.edu/bio/hiba-baroud



- Shizhe Chen
  - Deparment of Statistics
  - UC Davis, USA
  - https://statistics.ucdavis.edu/people/shizhe-chen

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Industry of the Futur @ CS

- Junior Chair: Human centered Explainable IA for Industry of the Futur
- Master of Science IA – Decision under Uncertainty and Predictive Maintenance
- Platform project
  - A production line with belt conveyor
  - Robot arms (one or more) with camaras that supports human collaboration and could be programmed to implement some computer vision algorithms
  - A communication module based on 5G that allows us to teach telecommunication used in industry (networked control for example)
  - A camara that allows implementing quality inspections based on computer visions
  - Simulation software that allows creating virtual models for the systems.

Joint us

- Weekly seminar
- Contact, Publications, News : http://rrcs.centralesupelec.fr/en

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