Why do we need resilience? and how?

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Chair on risk and resilience of complex systems

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Outline

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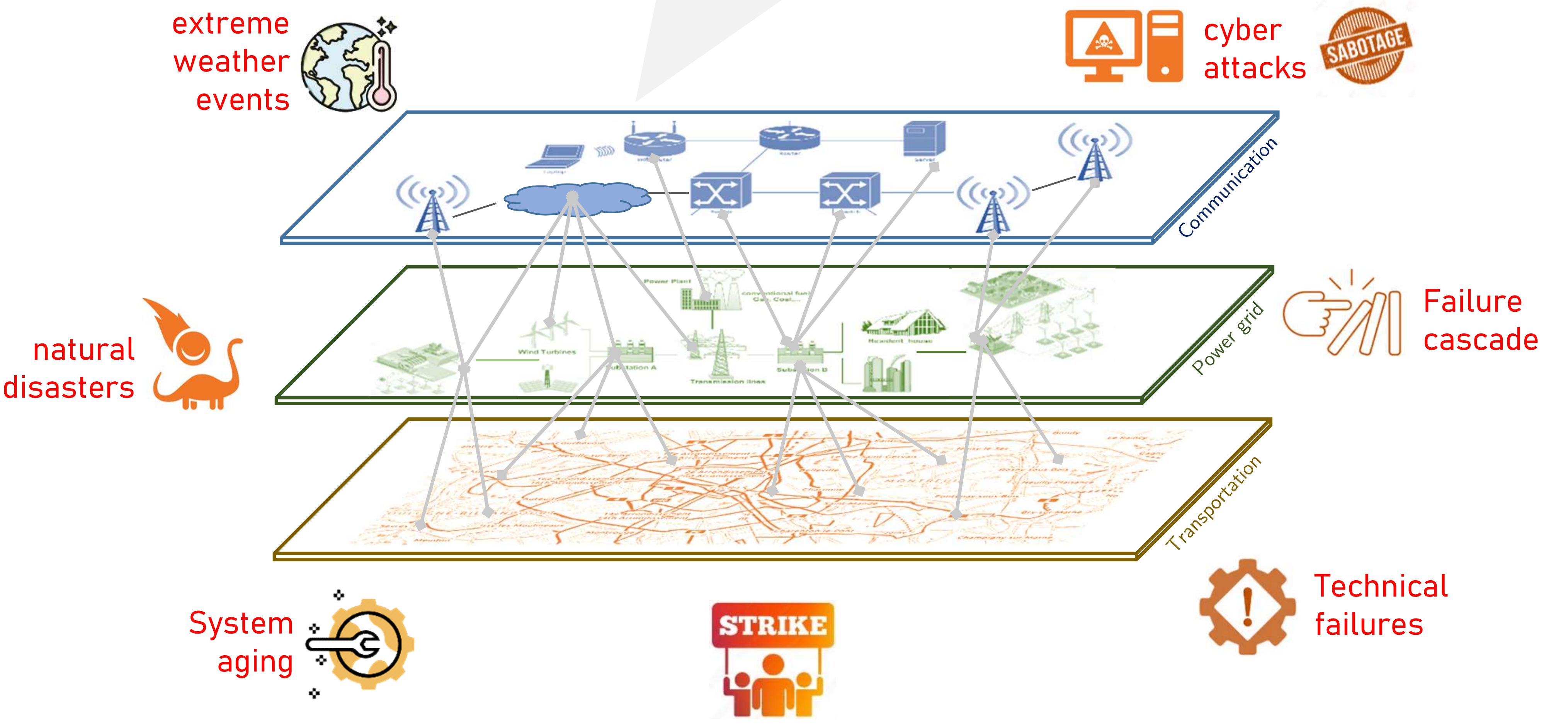
I. Why need resilience?

II. How? Two exemplary studies

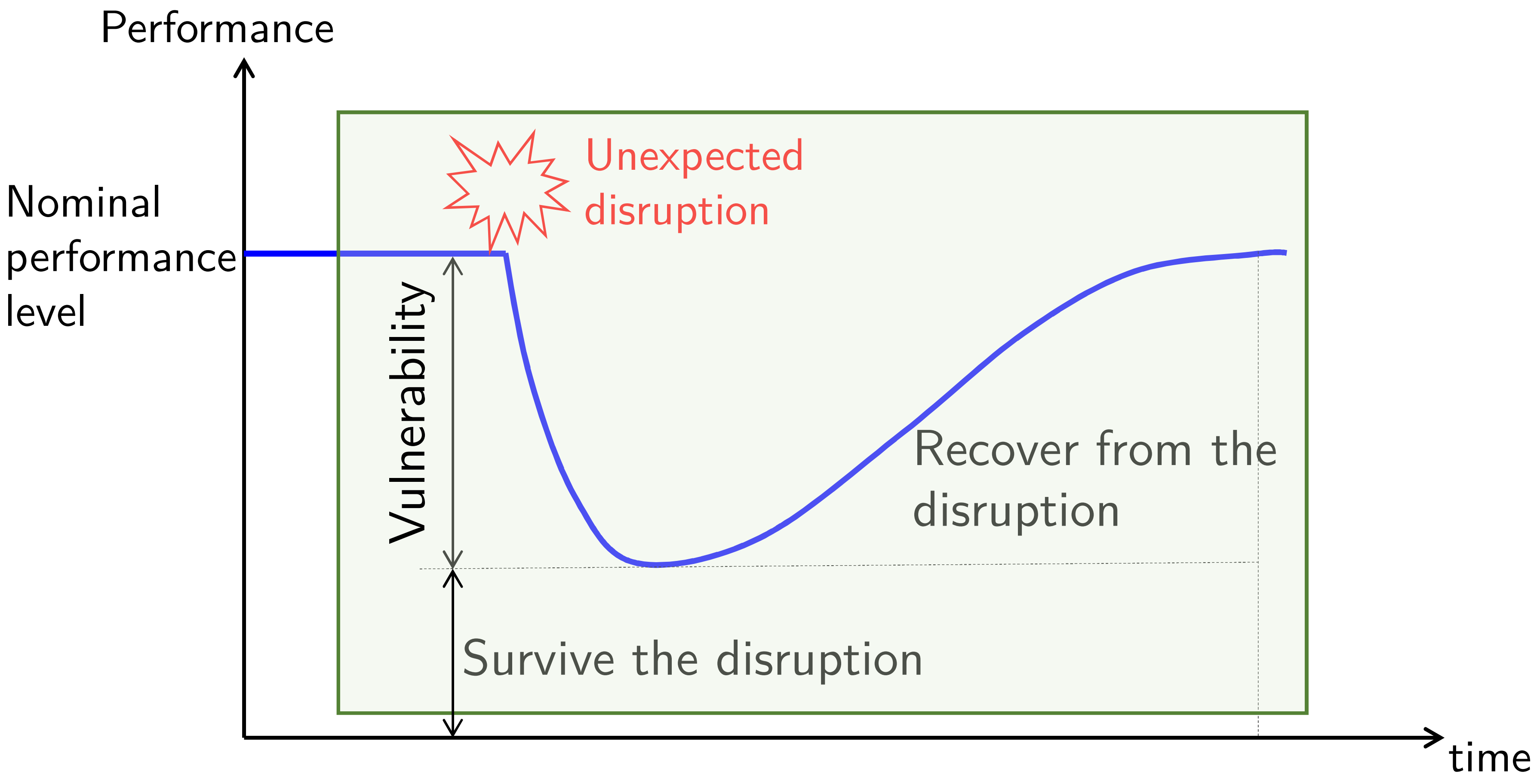
III. Challenges and perspectives

Interdependent networks & risk landscape

Hey, they have to be resilient !

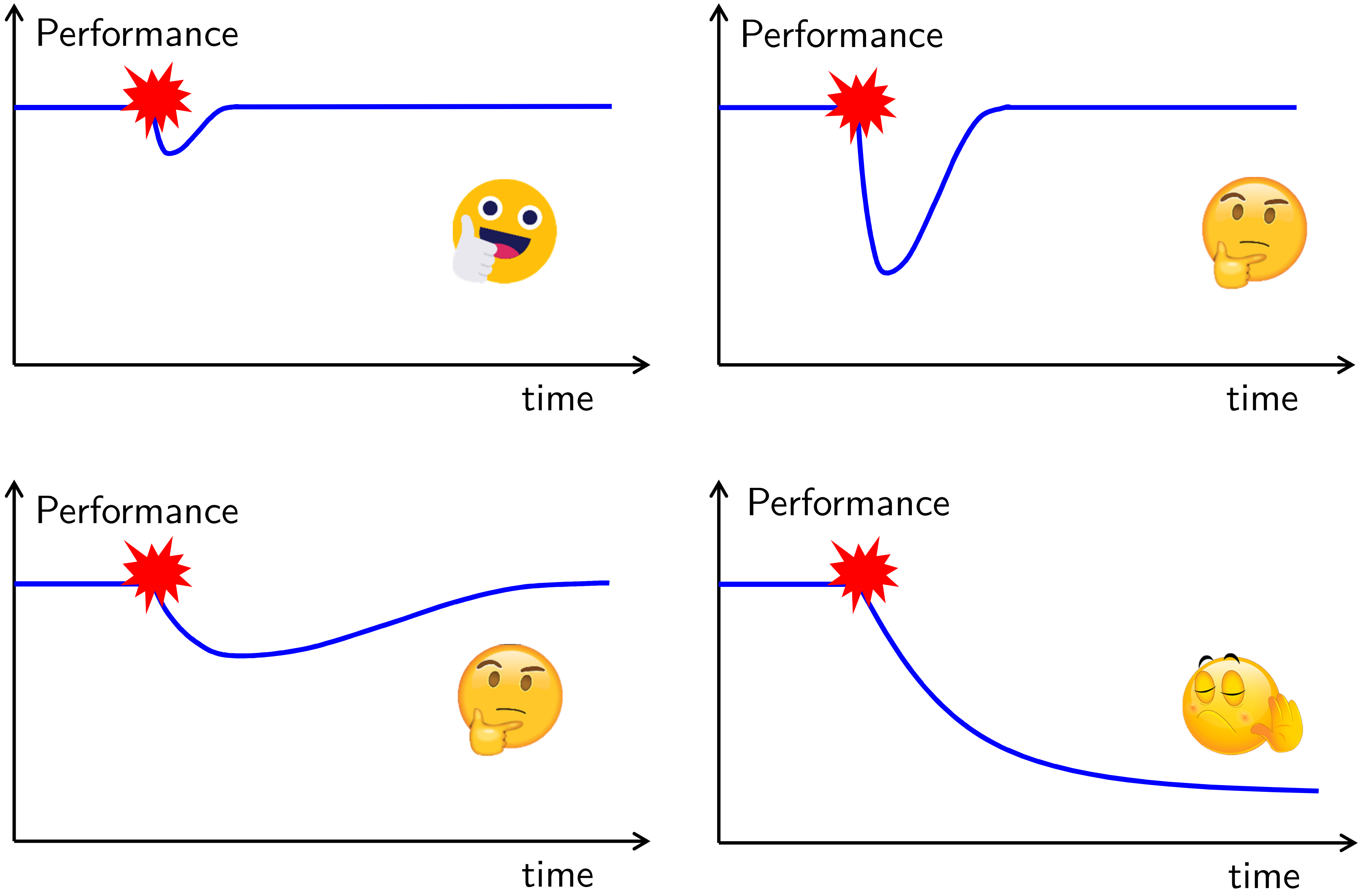


Resilience – the concept



Resilience = survivability + recoverability

Resilience – the concept



Resilience – the concept

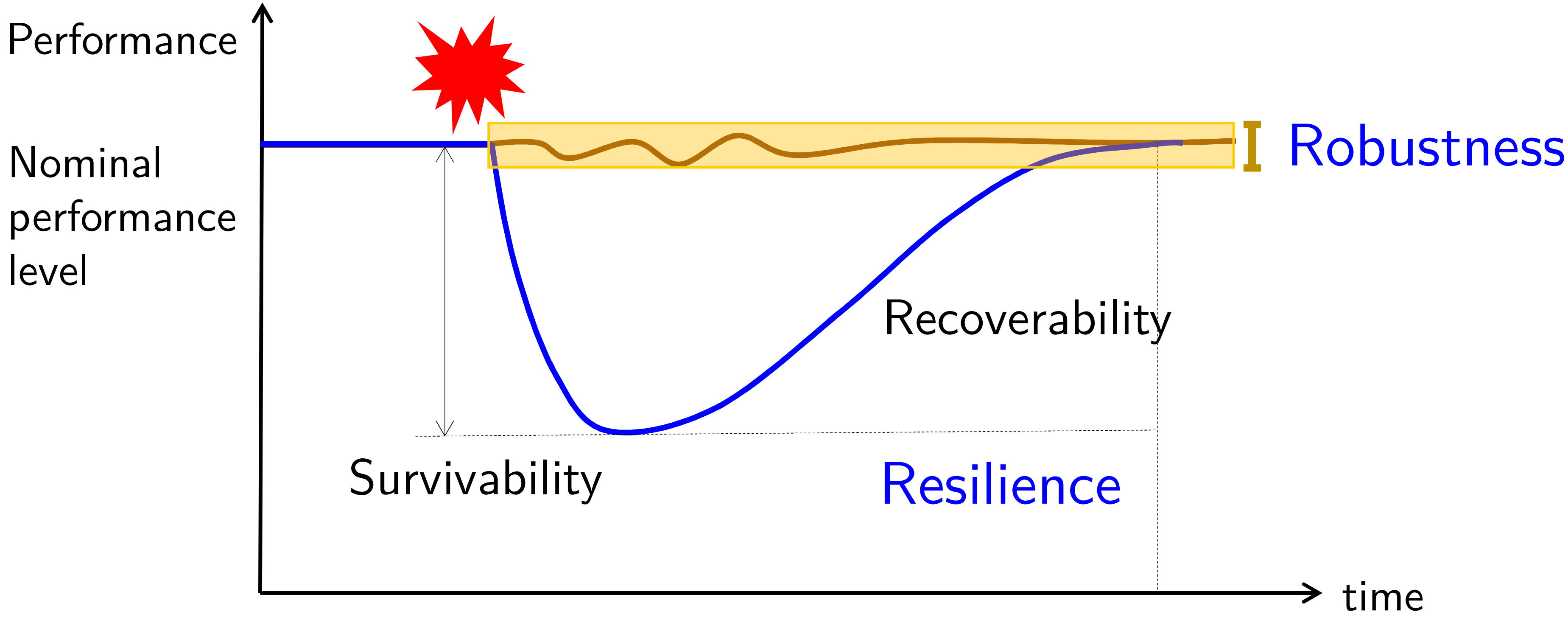
#Define resilience

Why we need resilient?

System-level "ilities": system attributes for hedging against **off-nominal conditions** (uncertainty)

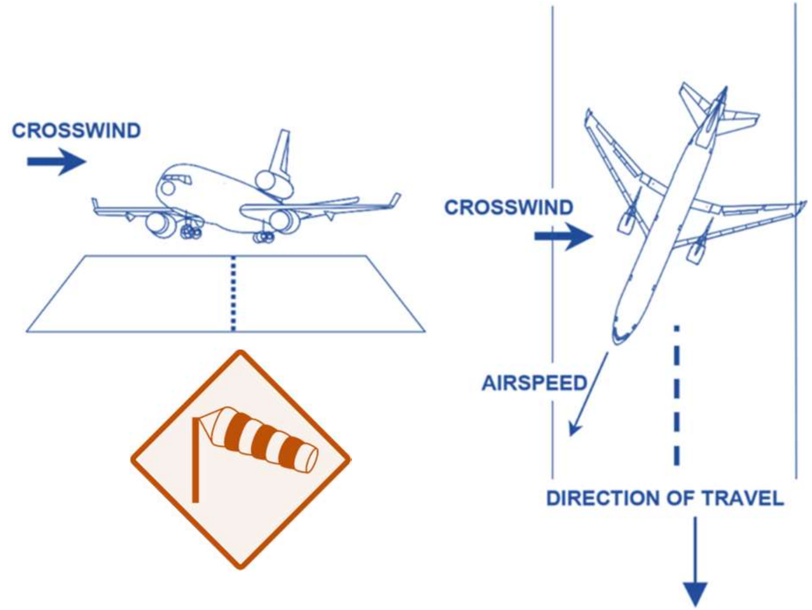
Resilience vs Robustness

- Robust systems are expected to satisfy (almost) the original performance requirements during specific disturbances



- Difficult/costly, appropriate for a small range of disturbances

Resilience vs Robustness



- Rains are frequent
- Designed to be robust to heavy rain (technically possible & cost-efficient)

- Severe crosswinds: occur less often, costly design
- A resilient response: diverted to the nearest suitable airport for landing, take alternative transports

Reliability vs Resilience ?

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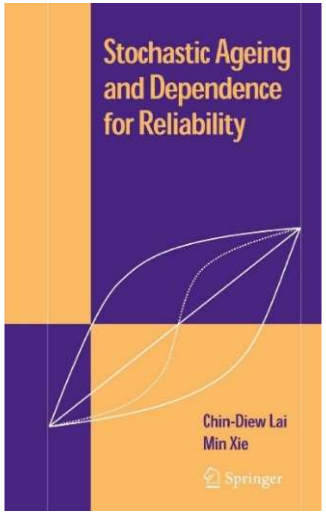
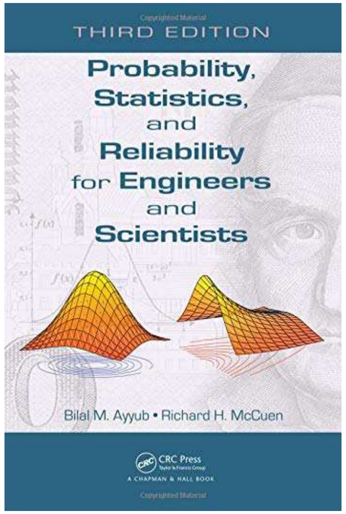
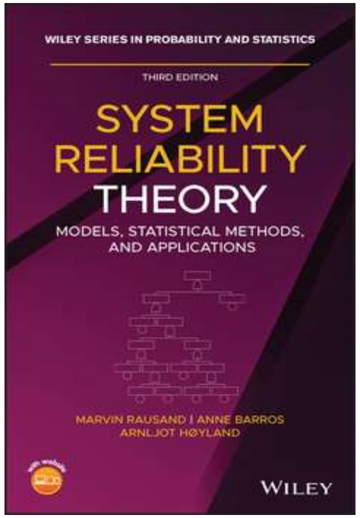
- **Reliability**: not conditional on the sources of failure





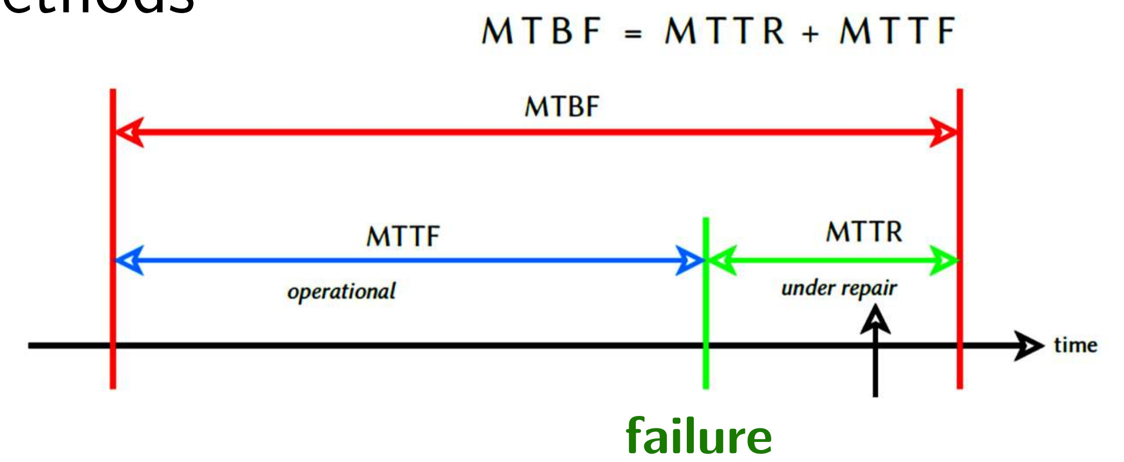


$$R(t) = \mathbb{P}(T \geq t)$$

$$\mathrm{MTTF} = \mathbb{E}[T]$$

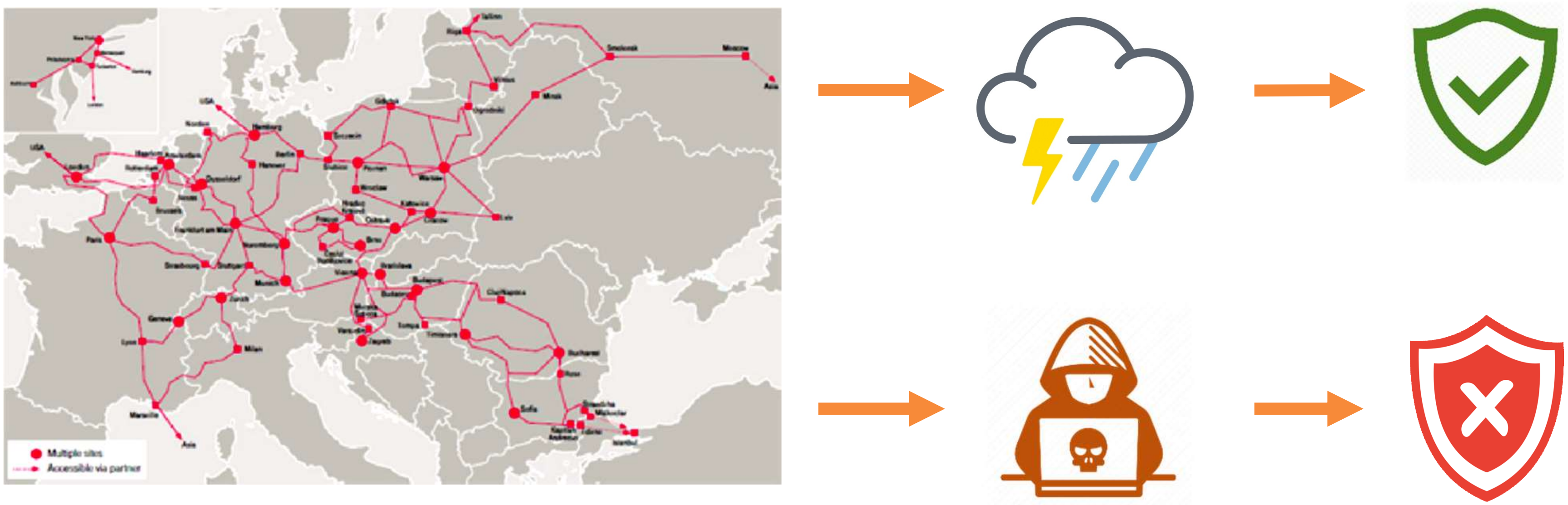
- Rely on the definition of failure v.s. non-failure
- Statistical & probabilistic methods

  $\rightarrow$ high frequency events



System resilience

- **Resilience** to what is important!



Reliability vs Resilience

Component

Simple system

complexity

Functionally equivalent, no space for resilience

Often the same interpretation

Reliability vs Resilience

Component

Simple system

Single system

complexity

Highly reliable engine & resilient system design

- Context becomes important, e.g., MTBF depends on what level of failure is deemed significant at the aircraft level.
- The distinction is one of degree

Reliability vs Resilience

Component

Simple system

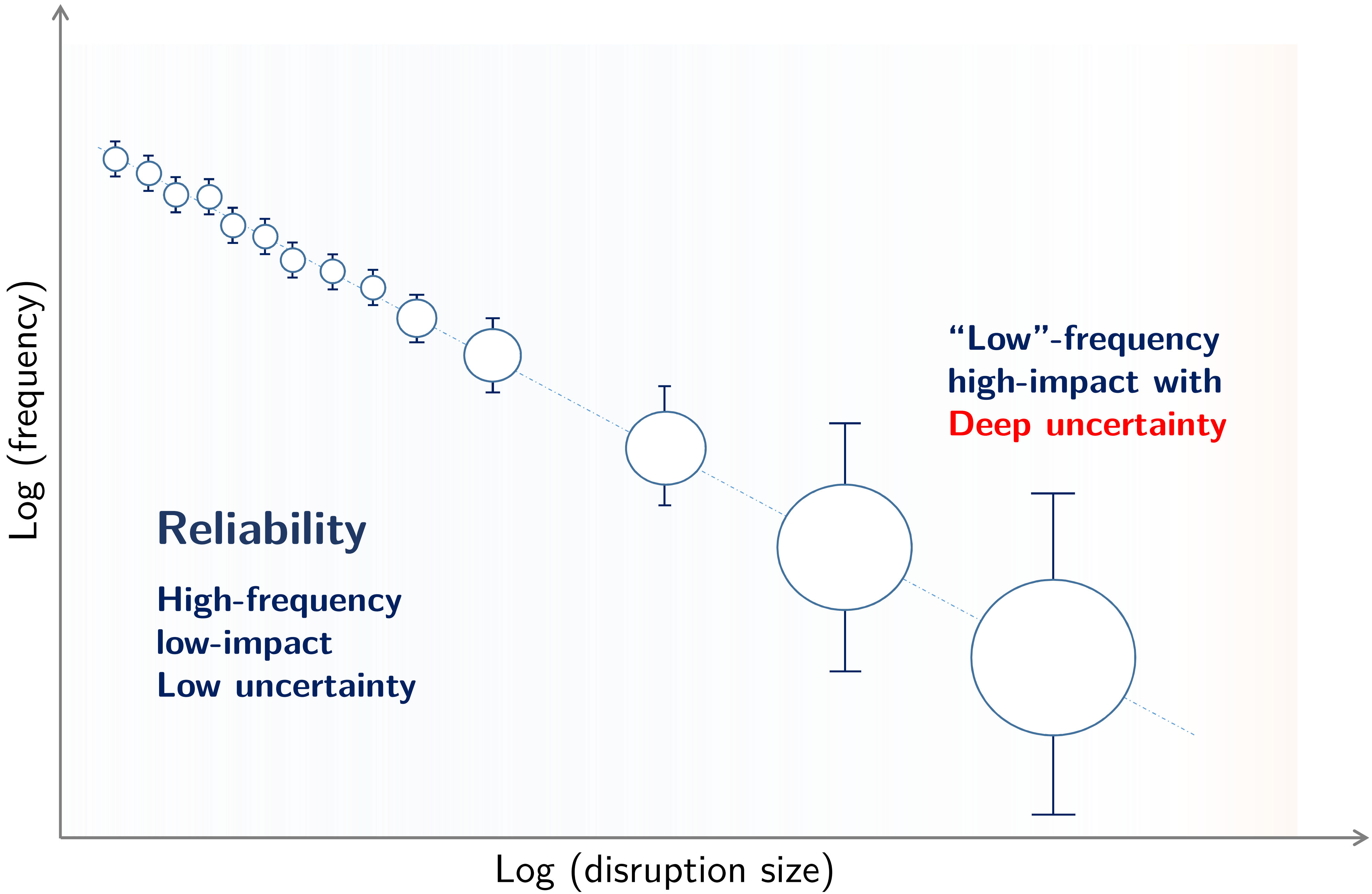
Single system

System of Systems

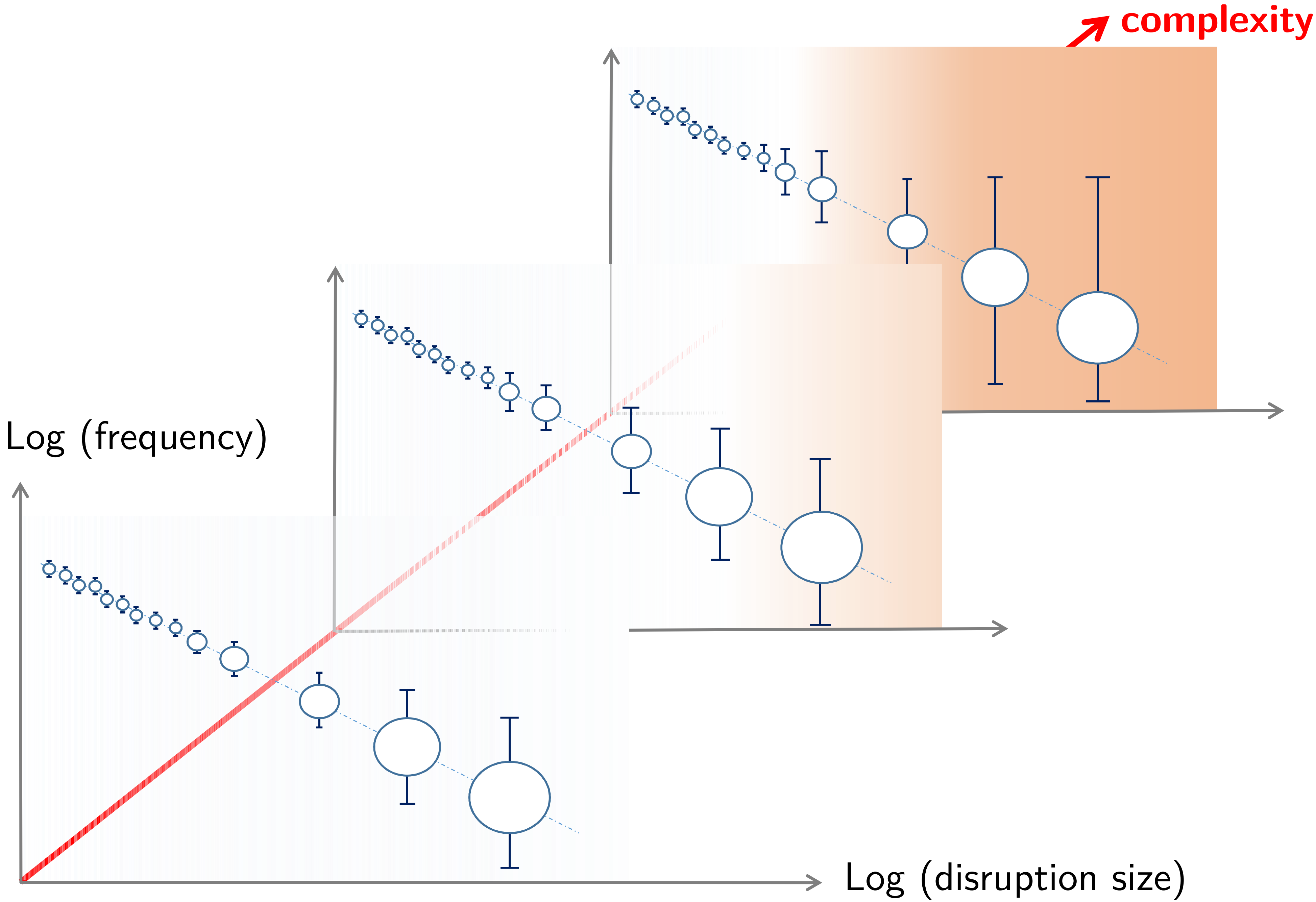
complexity

- **Non-trivial**: multi-dimensional performance, failure of which degree?
- A extremely reliable system is impossible /unrealistic
- Additional design/operational guidance by resilience to specific (HILF) events
- Absolute protection $\rightarrow$ anticipatory awareness, emergency planning, and efficient recovery decisions

Why reliability → resilience?



Why reliability → resilience?



II. How to build a resilient system / improve its resilience?

Engineering system resilience

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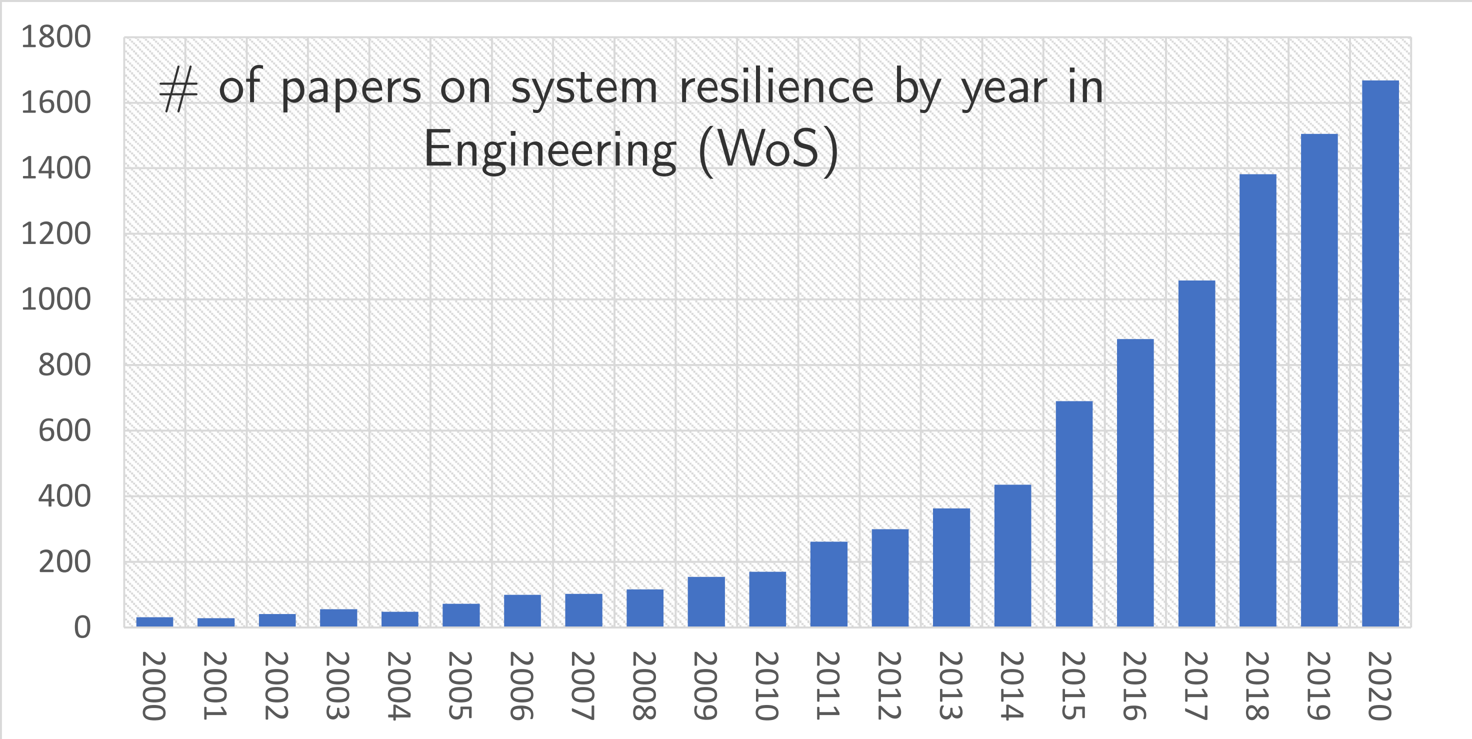
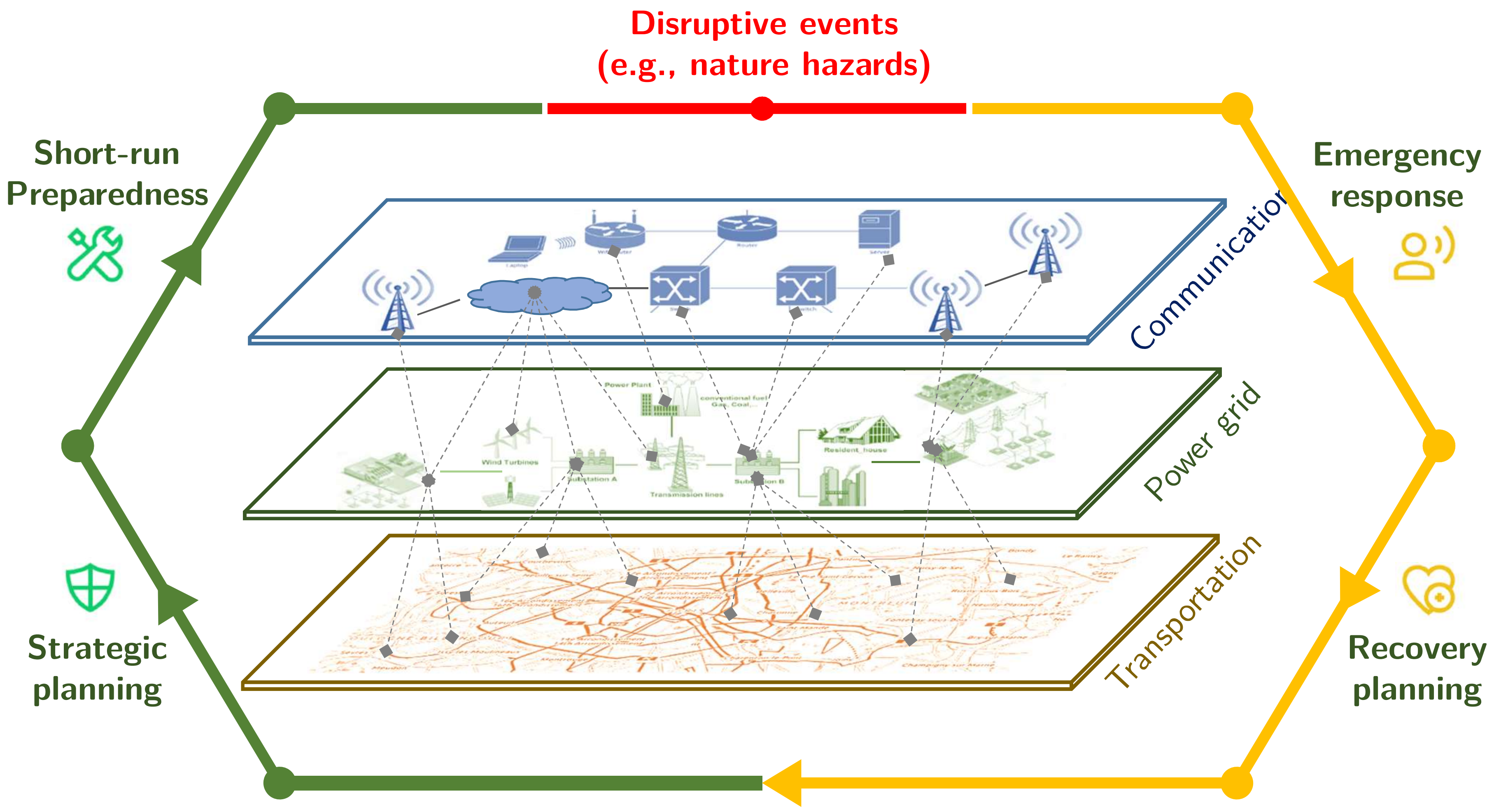


- Mostly focus on conceptualization, metrics, and assessment (Hosseini et al. 2016; Curt & Tacnet 2018)
- **Ultimate goal**: design and improve system resilience

Multi-stage framework

For resilience improvement



Exemplary studies

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Study 1: DRO-based coupling interface design for resilience

"A data-driven distributionally robust approach for the optimal coupling of interdependent critical infrastructures under random failures". *European Journal of Operational Research, under review*

Study 2: DRL for post-event service restoration

"Exploiting deep reinforcement learning for power grid recovery planning with uncertain repair time". *IEEE Transactions on Smart Grids, under preparation*

1. Coupling interface design for resilience

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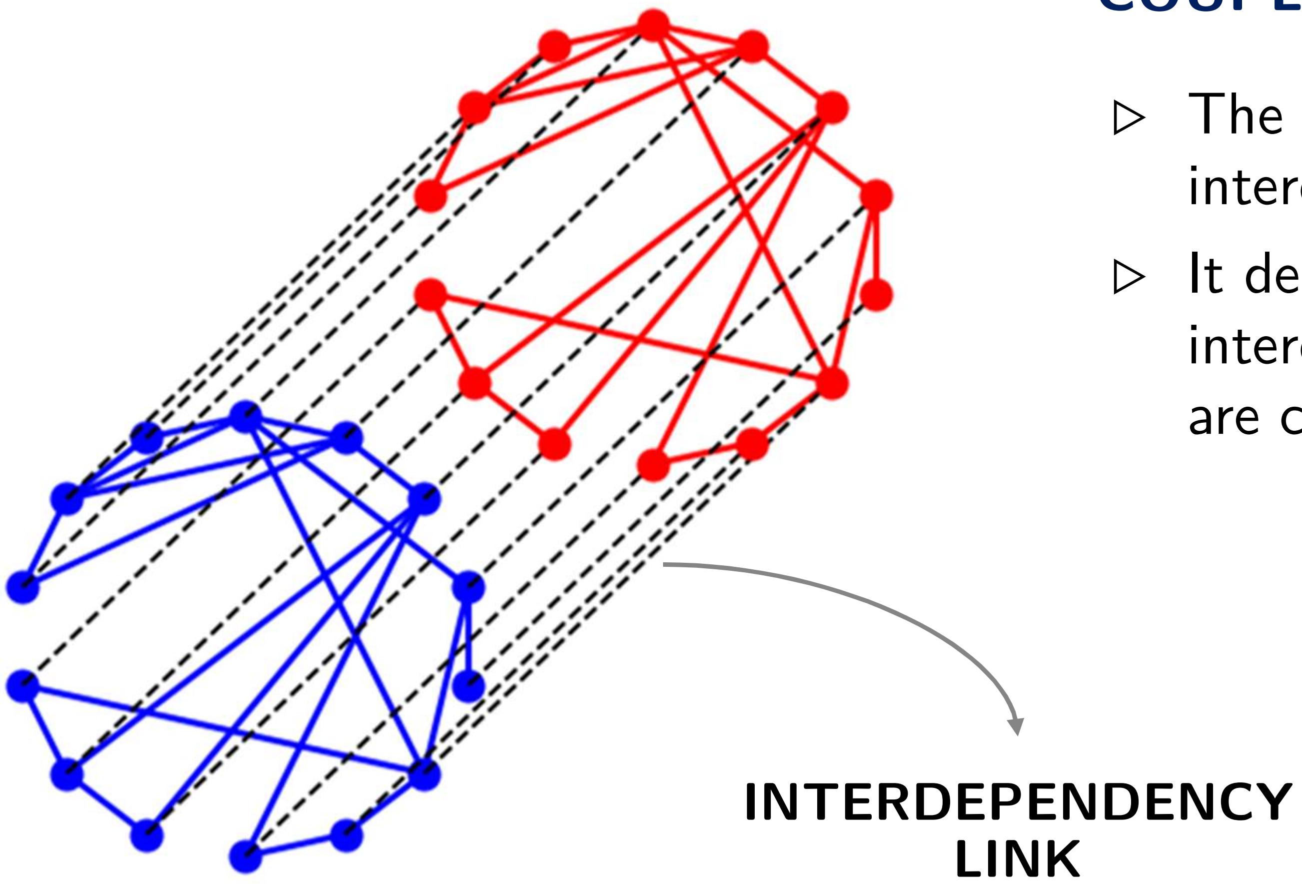
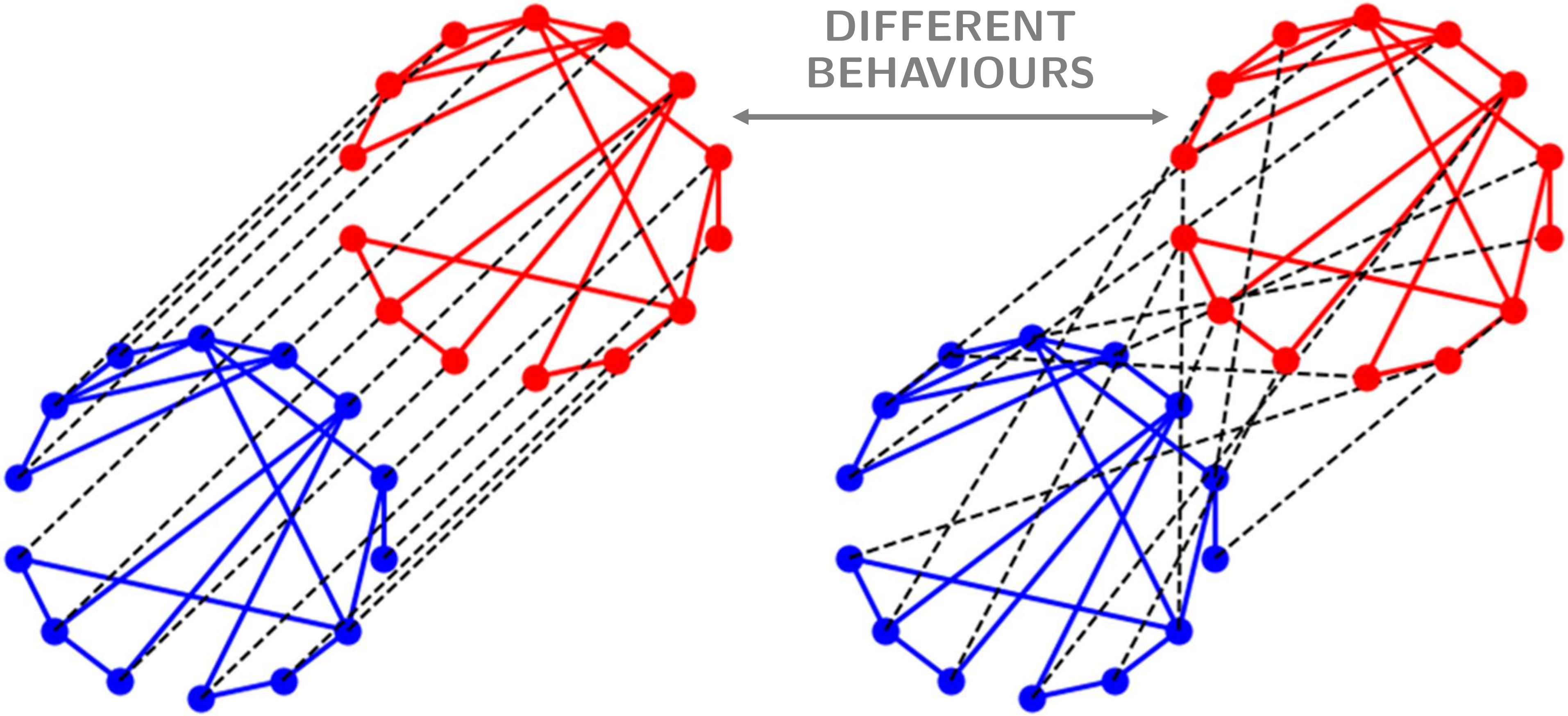


COUPLING INTERFACE

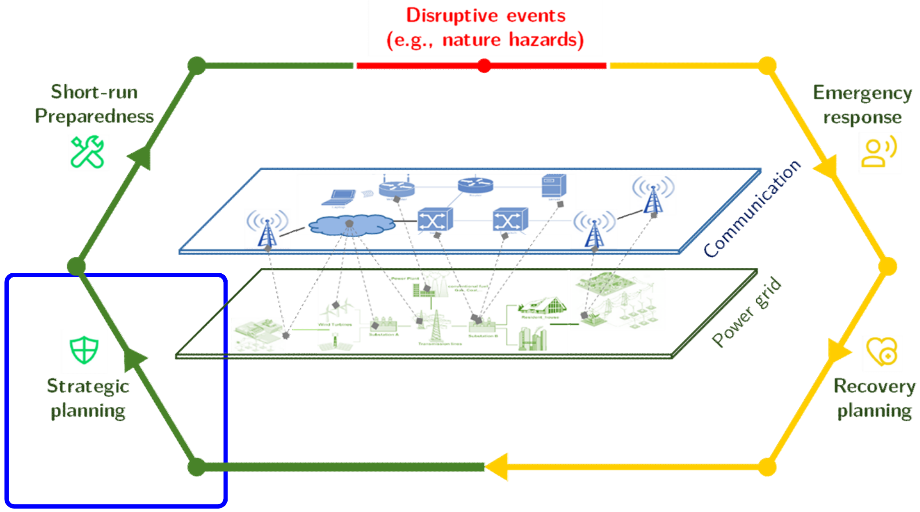
- ▷ The ensemble of interdependency links
- ▷ It defines how interdependent systems are coupled together

Coupling interface



Research question

- How to design the coupling interface between interdependent network systems?



- **Key challenges**:

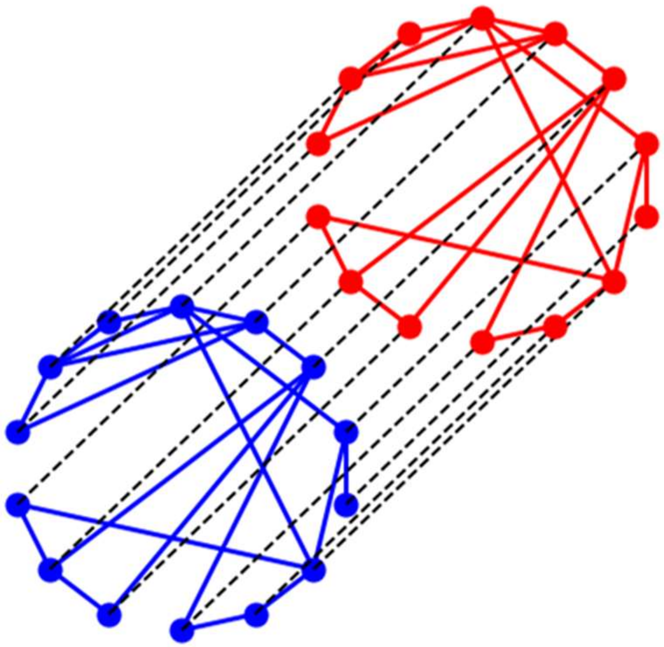
1) How to handle the (possibly deep) uncertainty of failure scenarios

2) Tractable models & effective solution methodologies?

Existing literature

Problem domain

- 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 Civan 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.

Existing literature

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Optimization models for similar problems

Recourse function

$$\mathbf{SP}:\max_{\boldsymbol{x}\in\mathbb{X}}\ \mathbb{E}_{\mathbb{P}}[\mathcal{Q}(\boldsymbol{x},\boldsymbol{u})]$$

Design variable

Failure scenario

$$\mathbf{RO}:\max_{\boldsymbol{x}\in\mathbb{X}}\ \min_{\boldsymbol{u}\in U}\ \mathcal{Q}(\boldsymbol{x},\boldsymbol{u})$$

Uncertainty set: feasible failure scenarios

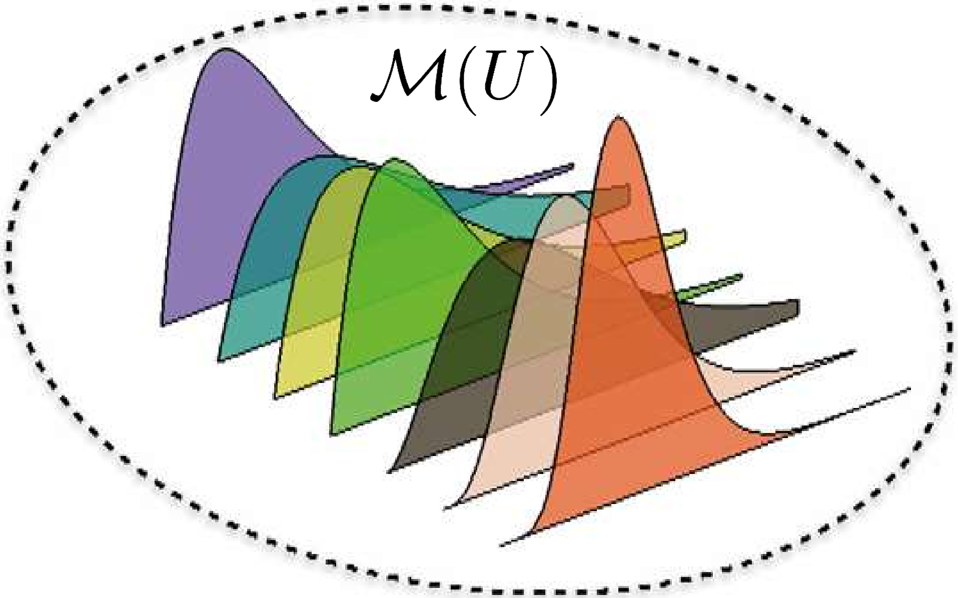
- Probability distribution of the set of feasible failure scenarios
- Difficult to estimate due to lack of data, environment variability, and rare events

- No need to estimate the probabilities of failure scenarios
- Too conservative/costly

Proposed distributionally robust approach

$$\textbf{SP} : \max_{\boldsymbol{x} \in \mathbb{X}} \; \mathbb{E}_{\mathbb{P}}[\mathcal{Q}(\boldsymbol{x}, \boldsymbol{u})]$$

$$\textbf{DRO} : \max_{\boldsymbol{x} \in \mathbb{X}} \boxed{\min_{\mathbb{P} \in \mathcal{M}(U)}} \mathbb{E}_{\mathbb{P}}\left[\mathcal{Q}(\boldsymbol{x}, \boldsymbol{u})\right]$$



Proposed DRO approach

- Ambiguity set

$$U = \left\{ \boldsymbol{u} \mid \boldsymbol{u} \in \{0,1\}^N, \|\boldsymbol{u}\|_1 \geq N - k \right\}$$

$$\mathcal{M}(U) = \{\mathbb{P} \in \mathcal{P}(U) : \ \mathbf{0} \leq \mathbb{E}[1 - \boldsymbol{u}] \leq \boldsymbol{\pi}^{max}\}$$

  - ▷ Set of multinomial distributions of the set of feasible failure scenarios
  - ▷ Upper bound on the marginal probability of each line to be failed
  - ▷ Risk-averse, but less conservative than RO

Solution strategy

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$$\max_{\boldsymbol{x}\in\mathbb{X}} \min_{\mathbb{P}\in\mathcal{M}(U)} \mathbb{E}_{\mathbb{P}}\left[\mathcal{Q}(\boldsymbol{x},\boldsymbol{u})\right]$$

$$\mathcal{Q}(\boldsymbol{x},\boldsymbol{u}) = \max_{\boldsymbol{h},\boldsymbol{\delta}} \boldsymbol{b}^\top \boldsymbol{h}$$
$$s.t.\ \boldsymbol{R}\boldsymbol{h} + \boldsymbol{W}\boldsymbol{\delta} \leq \boldsymbol{q} - \boldsymbol{H}\boldsymbol{x} - \boldsymbol{T}\boldsymbol{u}$$

Proposition 1: dual counterpart

$$\max_{\boldsymbol{x}\in\mathbb{X}} \min_{\boldsymbol{u}\in U} \mathcal{Q}(\boldsymbol{x},\boldsymbol{u}) + \sum_{n\in\mathcal{N}} \beta_n(1-u_n-\pi_n^{max})$$

Key observation: the support is a finite discrete set $U = \{\boldsymbol{u}^j\}_{j=1}^J$

Proposition 2: Equivalent monolithic MILP

Solution strategy

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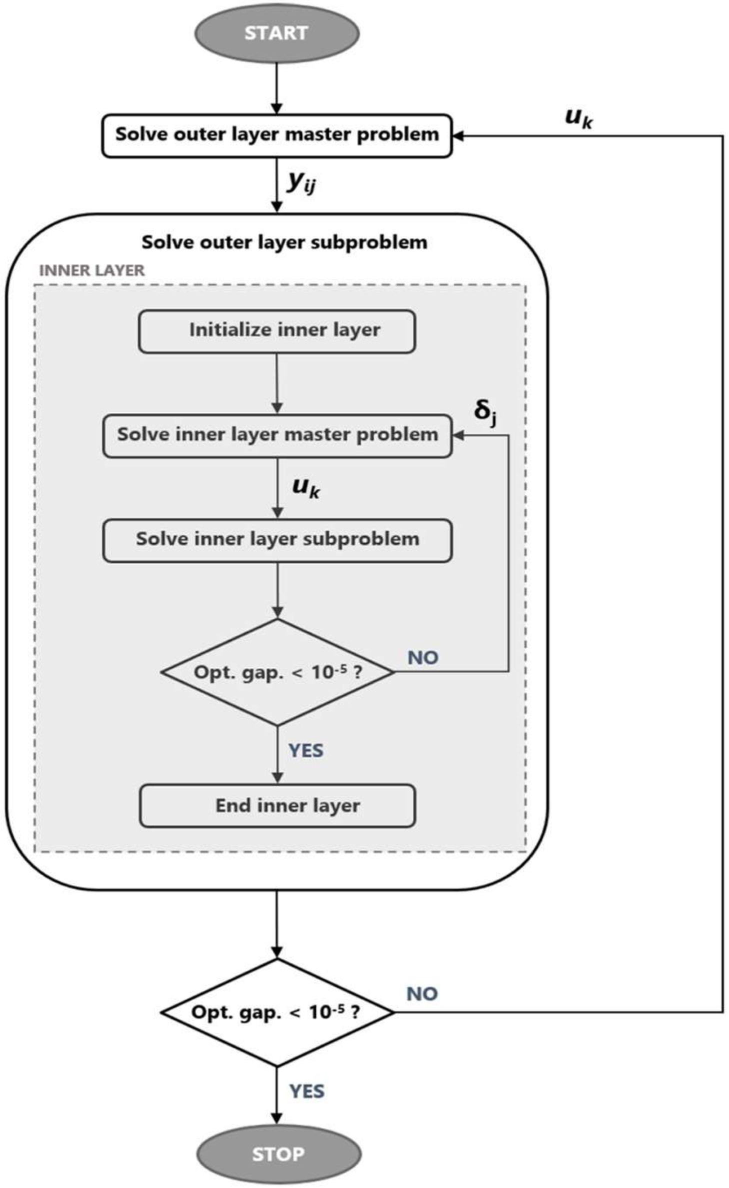
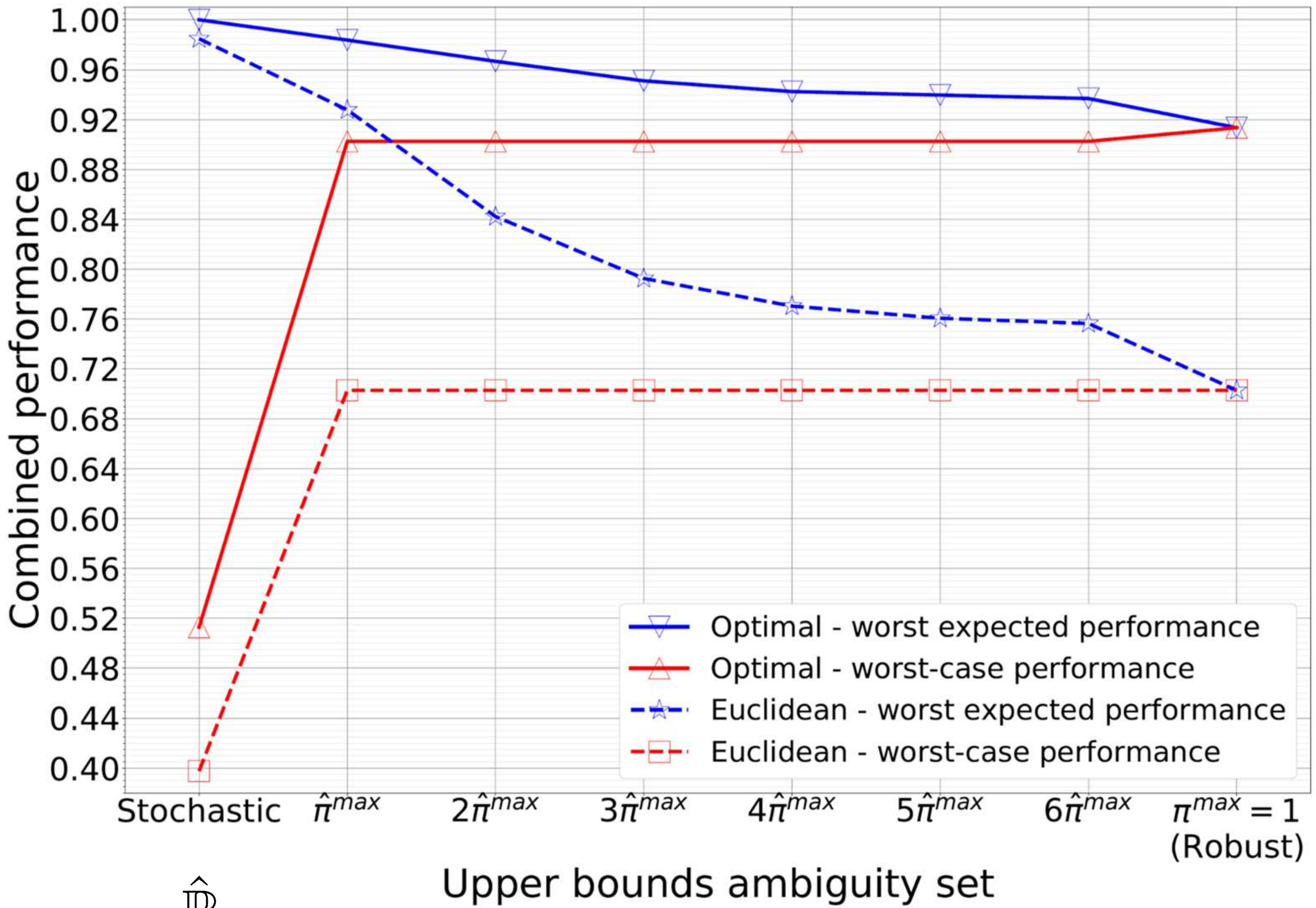
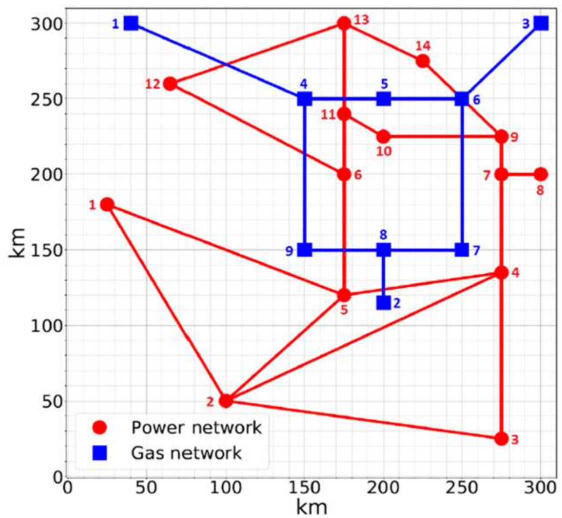
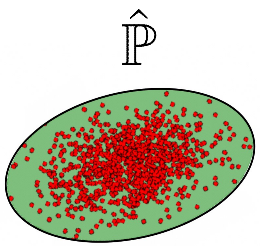
Decomposition strategy for solving the Equivalent monolithic MILP



Some results

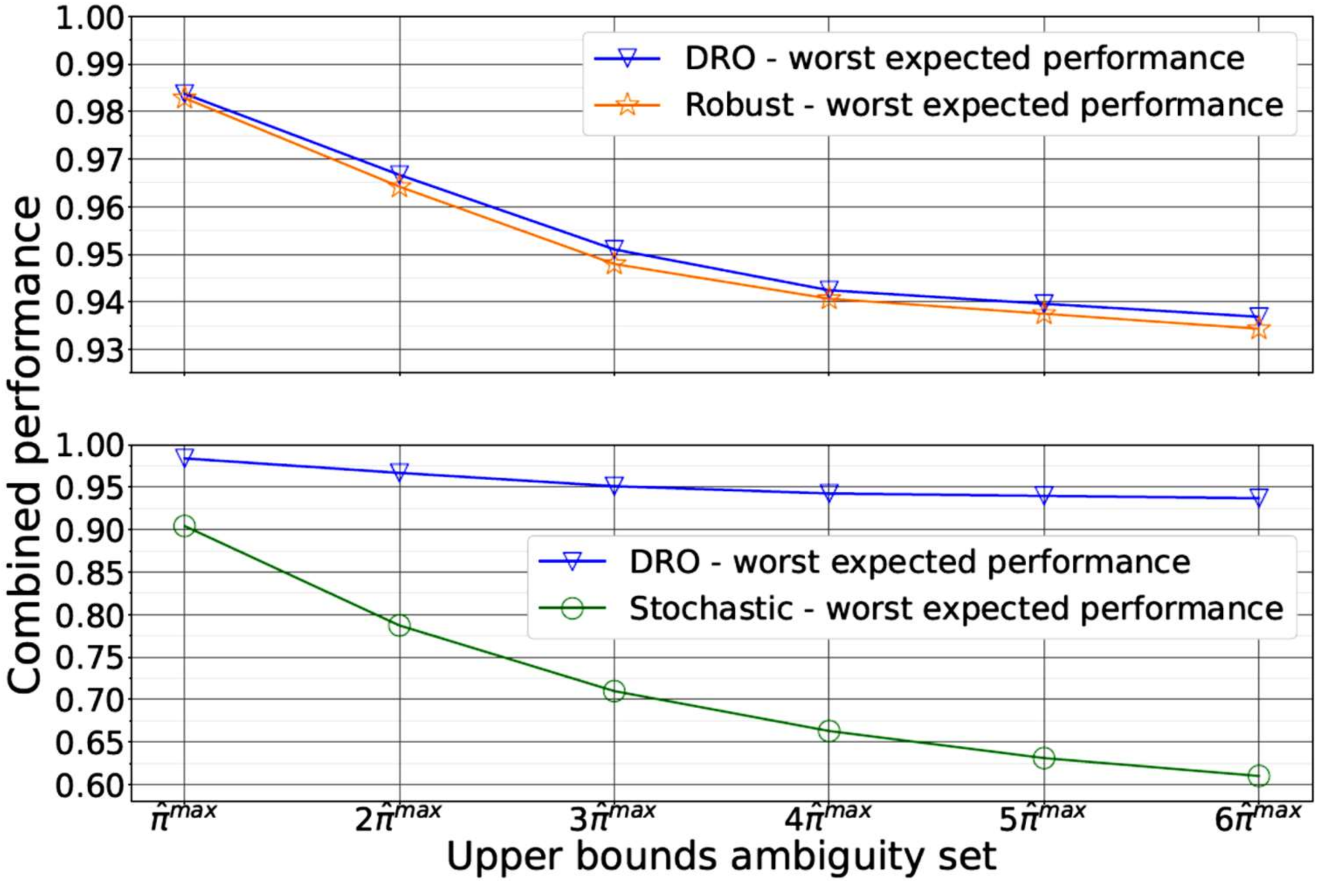






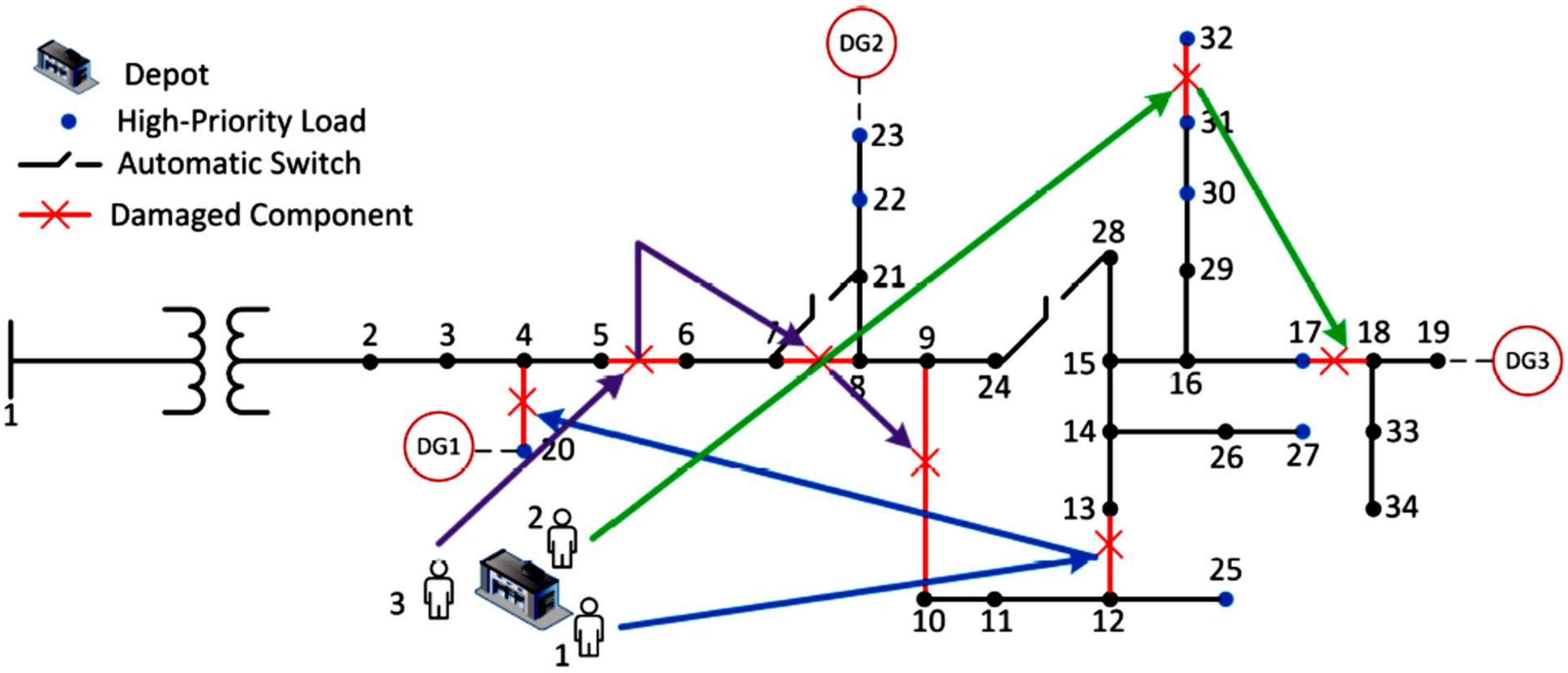
- ▷ Importance of the coupling interface design in ensuring the robustness of interdependent networks
- ▷ DRO provides satisfying solutions

Some results



- ▷ RO solutions are suboptimal in terms of their expected performance in the worst-case distribution $\mathbb{P}^\star$
- ▷ SP solutions perform very poorly when tested under $\mathbb{P}^\star$

2. Post-event service restoration

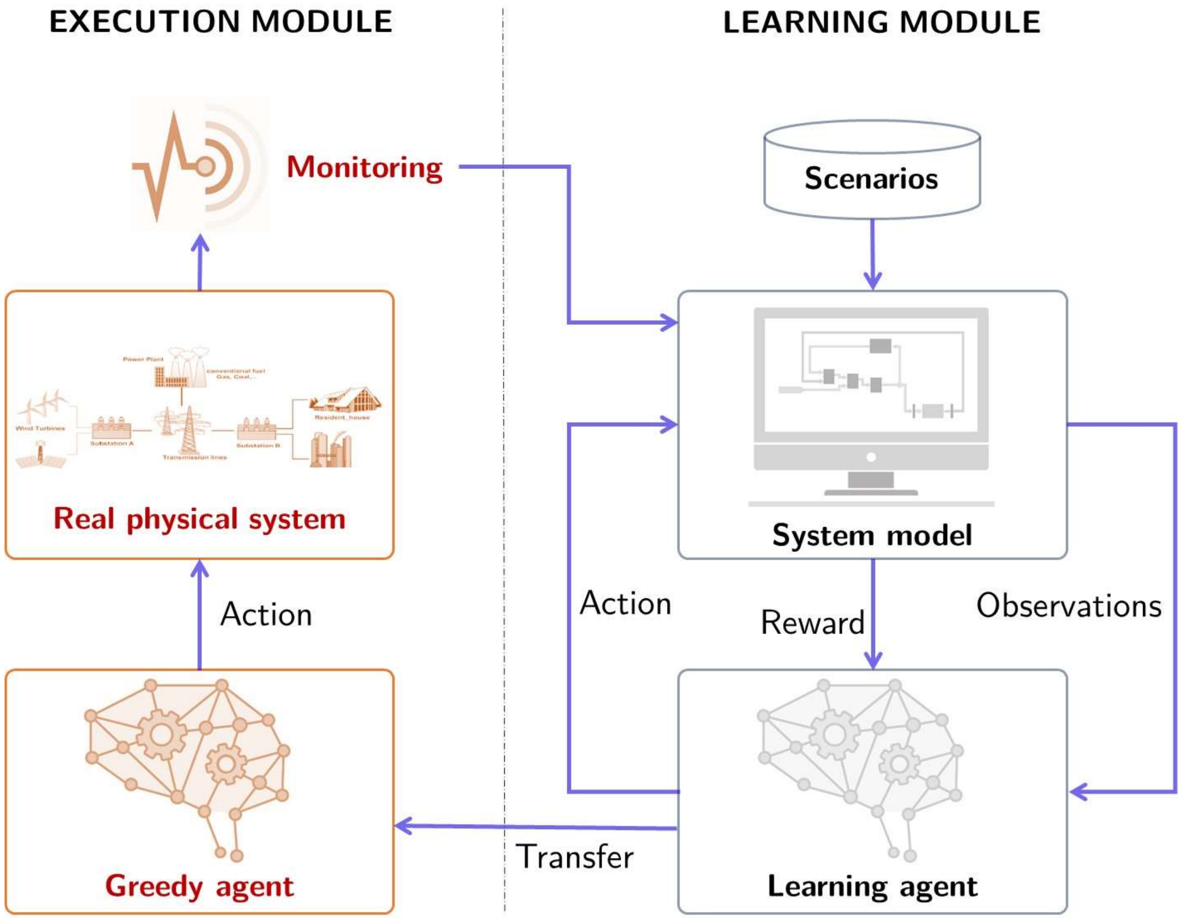


(Arif et al. 2018)

Question: how to schedule emergency & repair resources to speed up service restoration at the post-disruption phase?

Challenges

- Typically modeled by ILP, MILP, MINLP (Abhishek 2020)
- Combinatorial nature v.s. highly time-critical in ex-post stage
- Proposed remedy: deep reinforcement learning

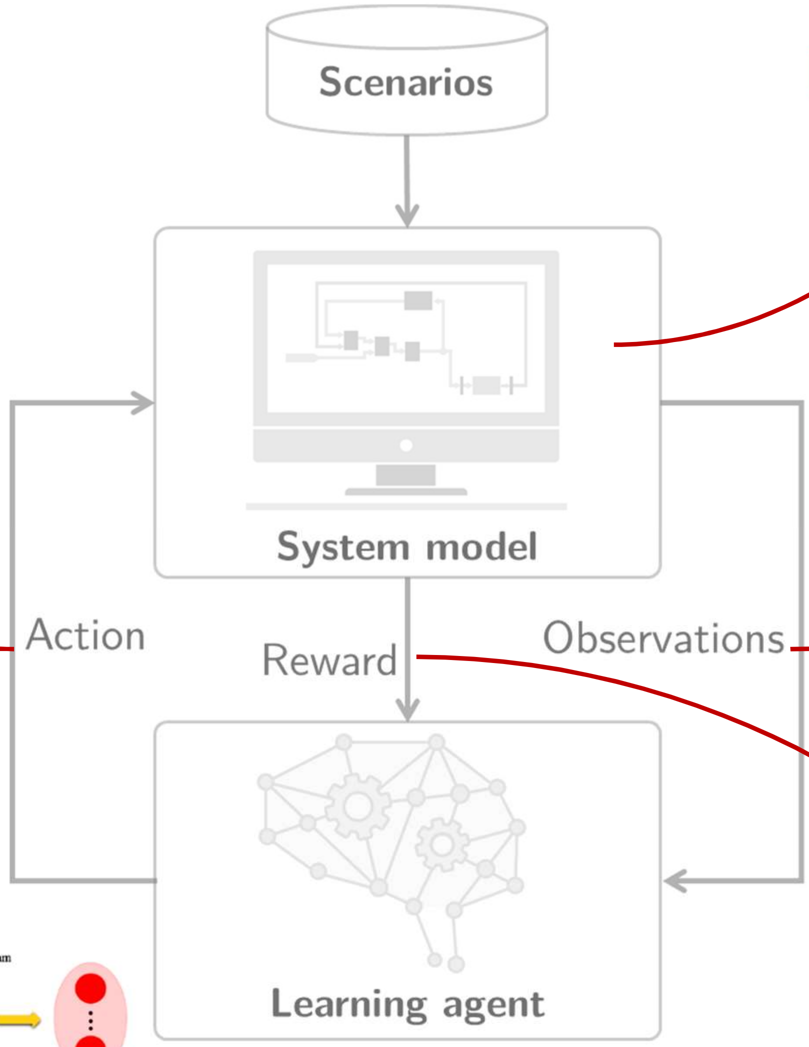


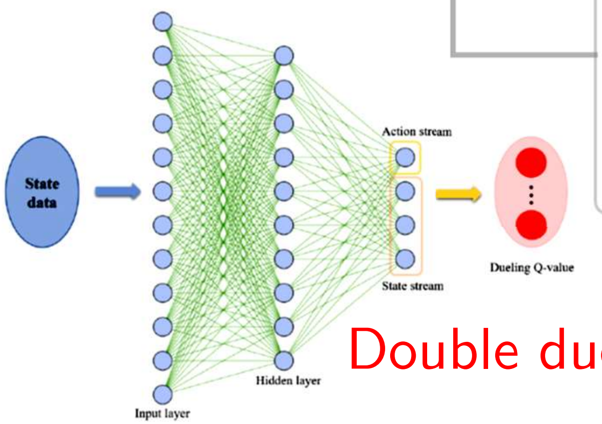
The DRL framework

DC-OPF $\mathcal{R}(\boldsymbol{s})$

Next component to be repaired

$$\boldsymbol{s} = \underbrace{[0, 1, 0, \ldots, 1]}_{\text{availability}}$$

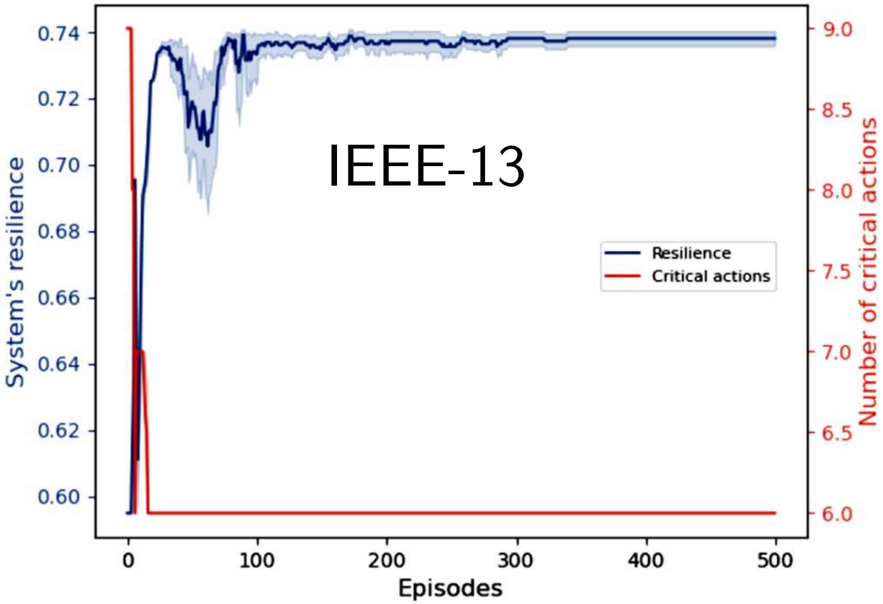


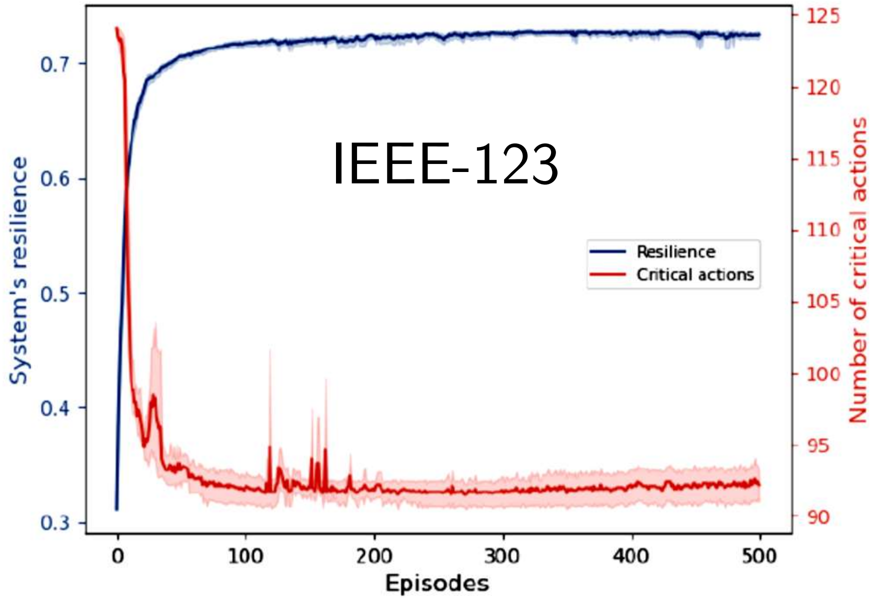


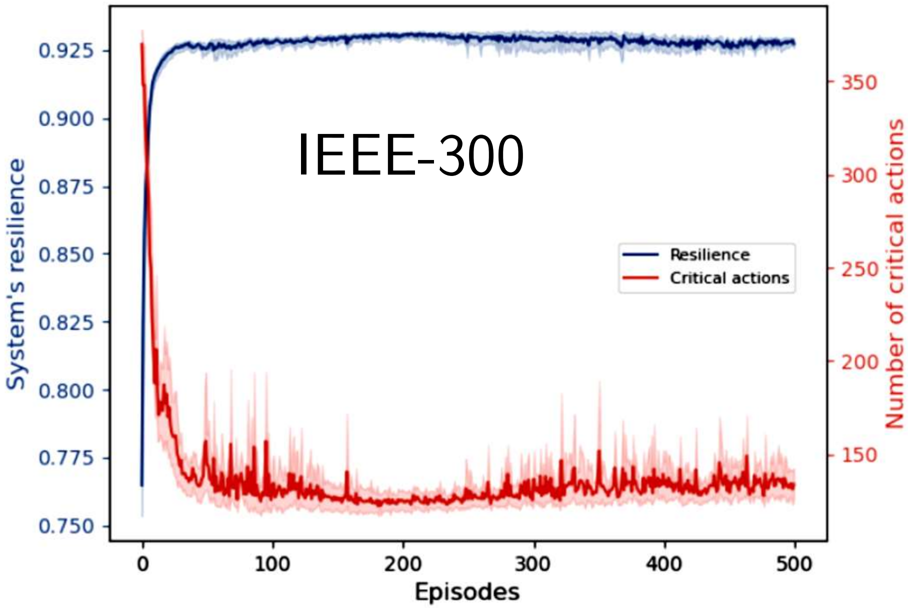
Double dueling DQN

$$R(\boldsymbol{s}, a, \boldsymbol{s}') = \mathbb{E}_{T_a}\left[\frac{\mathcal{R}(\boldsymbol{s}') - \mathcal{R}(\boldsymbol{s})}{T_a}\right]$$

Some results



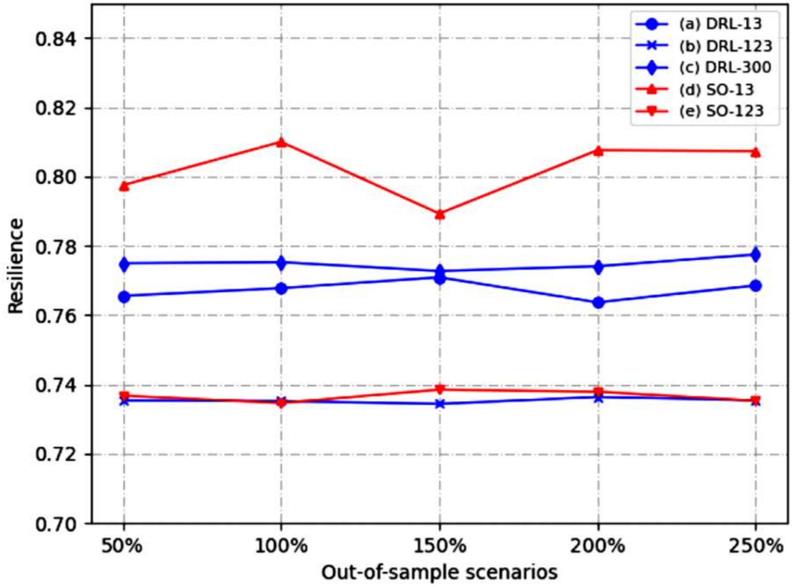




Some results

Trained DRL VS Stochastic Optimization

System	Method	Resilience	Actions	Time
13-nodes system	DRL	0.7714	6	0.1845s
	SO	0.8022	6	3.67s
123-nodes system	DRL	0.7386	90	11.66s
	SO	0.7371	92	24.7h
300-nodes system	DRL	0.9289	133	85.39s
	SO	None	None	None



- Near optimal performance with much less computational time
- More stable out-of-sample performance

III. Challenges & Perspectives

Challenges & perspectives

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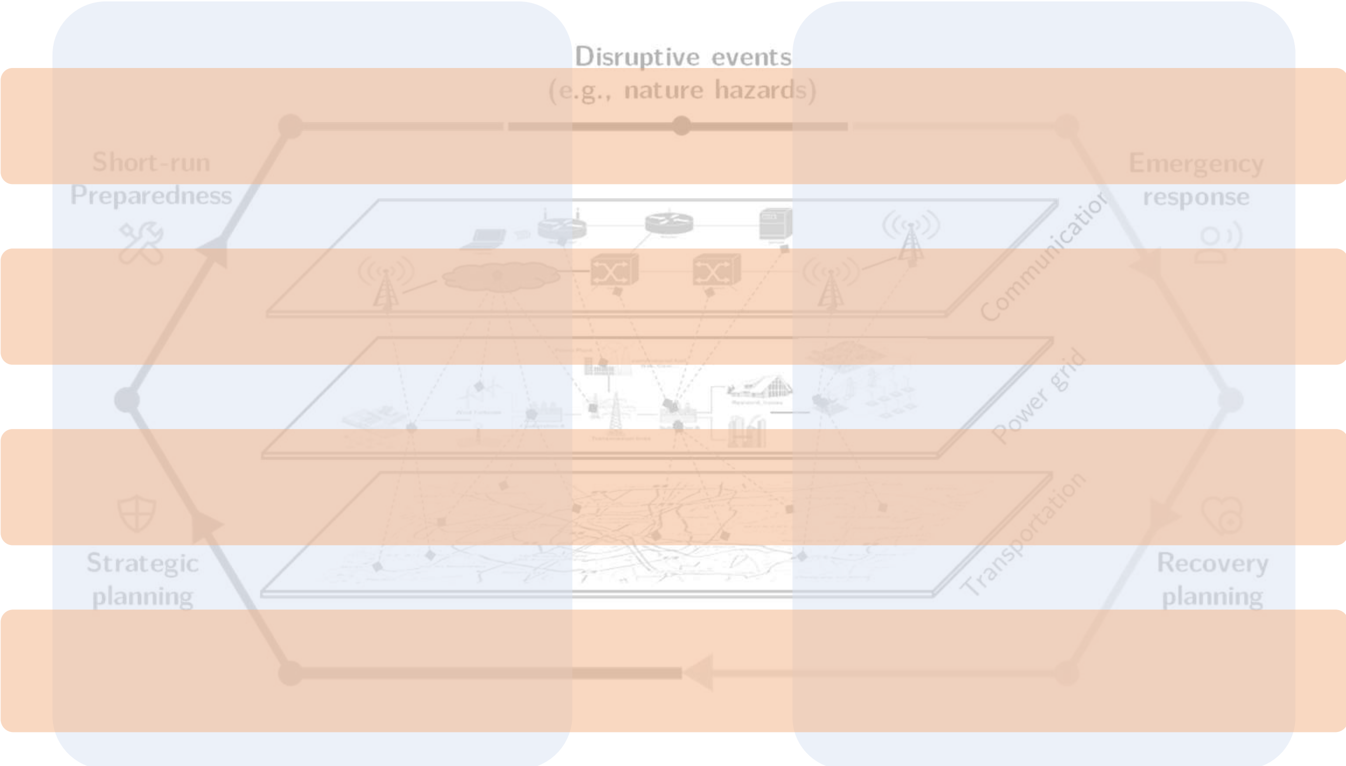
Problem domain

Solution robustness

Efficient & scalable



Model validation

Dynamic / stochastic interdependency

Multi-phases tradeoff

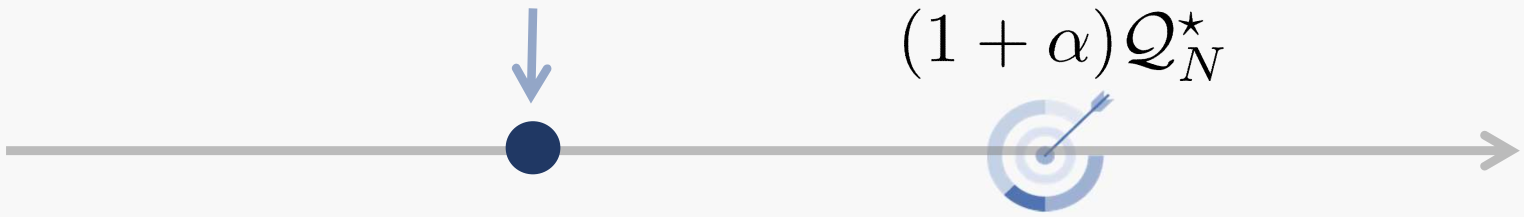
Multi-risks tradeoff

Algorithmic domain

Uncertainty: robust satisficing

"Contentment is the Greatest Wealth." - The Buddha

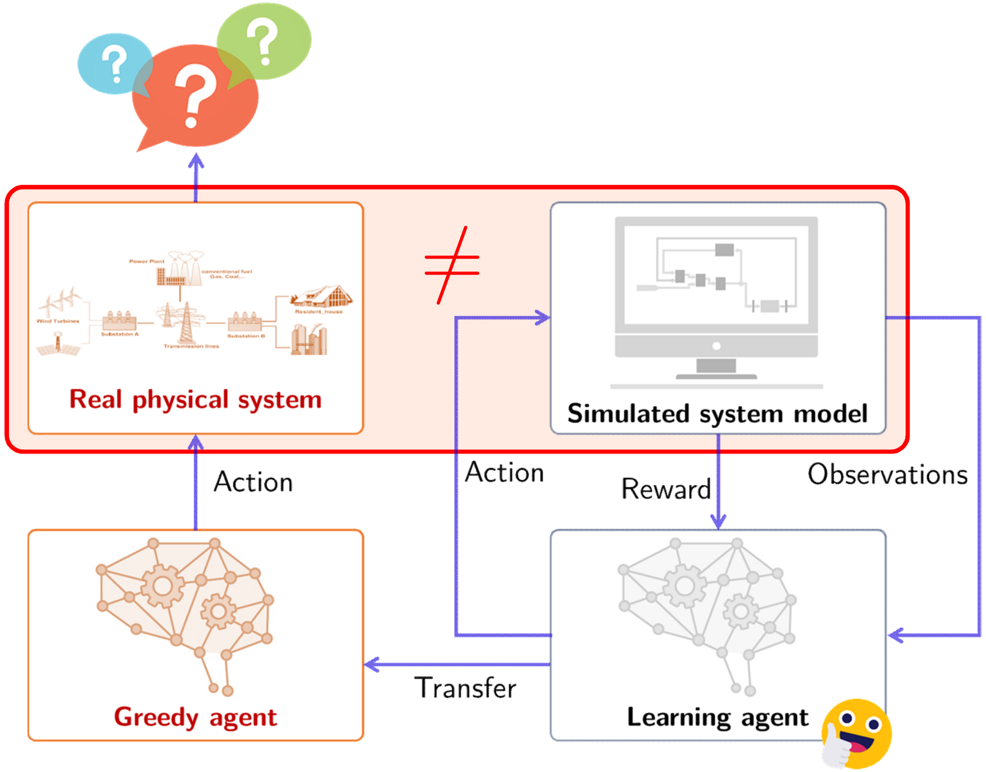
$$\mathcal{Q}_N^\star = \min_{\boldsymbol{x} \in \mathbb{X}} \mathbb{E}_{\mathbb{P}^N}\left[\mathcal{Q}(\boldsymbol{x}, \boldsymbol{\xi})\right]$$



$$\begin{aligned} \max_{\boldsymbol{x} \in \mathbb{X}} \ & \epsilon \\ \text{s.t. } & \mathbb{E}_{\mathbb{P}}\left[\mathcal{Q}(\boldsymbol{x}, \boldsymbol{\xi})\right] \le (1+\alpha)\mathcal{Q}_N^\star, \\ & \forall \mathbb{P} \in \hat{\mathcal{P}}_N(\epsilon) \end{aligned}$$

Ex-post stage

- **Simulation-to-reality gap**



→ Distributional RL with risk-averse measures (Dulac-Arnold, G., D. Mankowitz, and T. Hester, 2019)

- **Trustfulness:** RL & Numerical Optimization

Takeaway message

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- System complexity and constant "surprises" call for resilience
- Multi-phase & multi-dimension
- Prescriptive methods (e.g., optimization, RL) provide promising ways to go
- Many challenges remain: many exciting works to come!

Thanks for your attention!

Chair Risk and Resilience of Complex Systems

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