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Network robustness under massive failures: relevant metrics analysis and simulation

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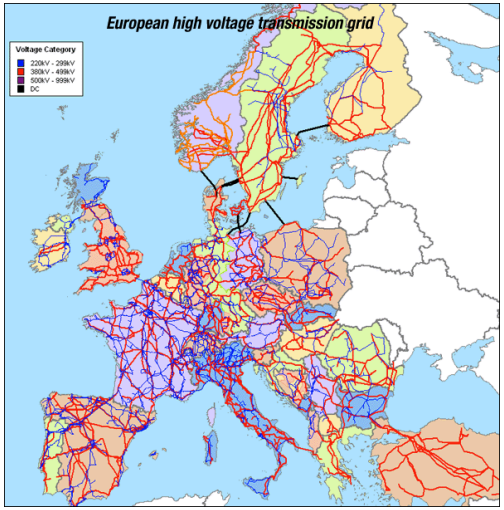
Contents

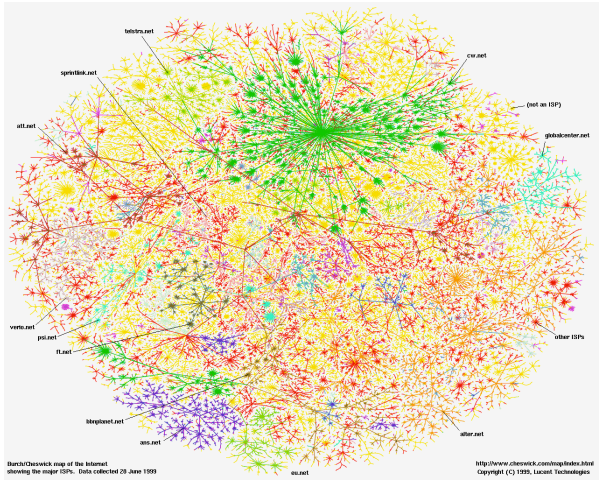
- Motivation
- The robustness concept and metrics
- Modelling multiple failures
- Robustness Computation mechanism
- Simulation scenario and some results
- Conclusions & future work

Motivation

London's underground



European power grid



The Internet

http://visualign.wordpress.com/2012/07/11/london-tube-map-and-graph-visualizations/

www.geni.org

www.cheswick.com

Robustness concept

Robustness (*robustus* / *robur*), means “oak” in Latin, being the symbol of strength and longevity in the ancient world.

“Robustness is the ability of a network to continue performing well even when it is subject to failures or attacks.”

Robustness computation relies on graph theory, it is mainly centered on graph connectivity

Robustness metrics

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- **Structural**
  (based on classic graph properties)
  - Average nodal degree, Finding paths
  - Connectivity & fragmentation
- **Centrality**
  (it locates the most “important” nodes/links)
  - Degree, Betweenness, Spectral properties, Eigenvectors, …
- **Dynamic/Functional**
  (Considering the expected performance of existing services)
  - Throughput, link occupancy, …

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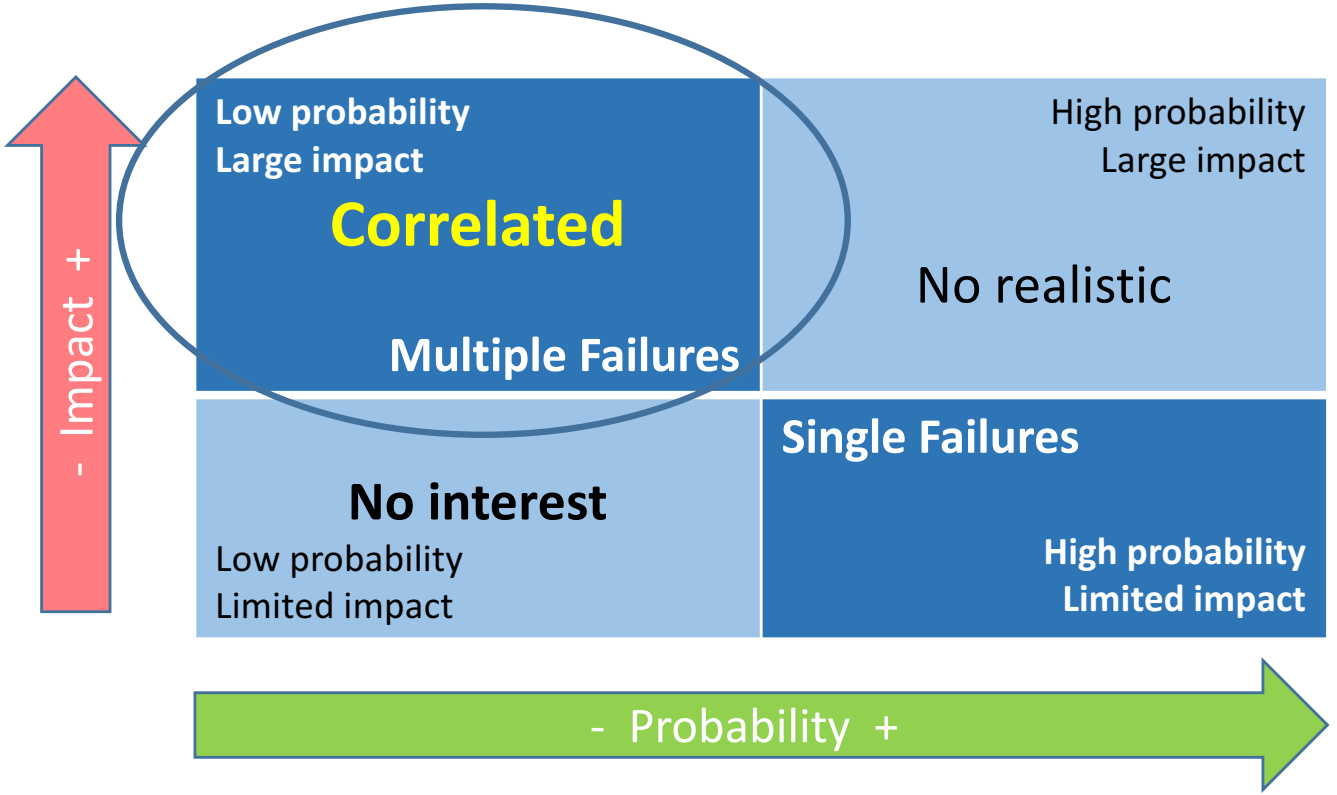
Single vs. Multiple failures



Multiple failures happen rarely **but their consequences are too costly**

Large-scale failure: a multiple failure in which a significant portion of network elements are affected by failures, all related to a **single** cause.

Resilient communication services protecting end-user applications from disaster-based failures (RECODIS)
COST Action **CA15127**

WG4 Malicious human activities

1. **Measures** to evaluate vulnerability of communication networks to malicious human activities
2. Techniques of **network design** / update of characteristics of existing network architectures to improve their resilience against malicious human activities
3. **Algorithms of resilient routing** (and routing metrics) to assure resilience of communication paths to malicious human activities Robustness metrics
4. **Advanced topics** in communication networks resilience under malicious human activities

Modelling multiple failures

Dynamic failures *occur along of time*

- *There is a **cause** that triggers the **propagation** (**correlated** failures)*
- On top of random, there are other **type of "attacks":**
  - *Targeted*
  - *Epidemics*
  - *Cascading*
  - *Others*

Dynamic scenarios: **targeted**

They are normally provoked by malicious attacks (human driven)

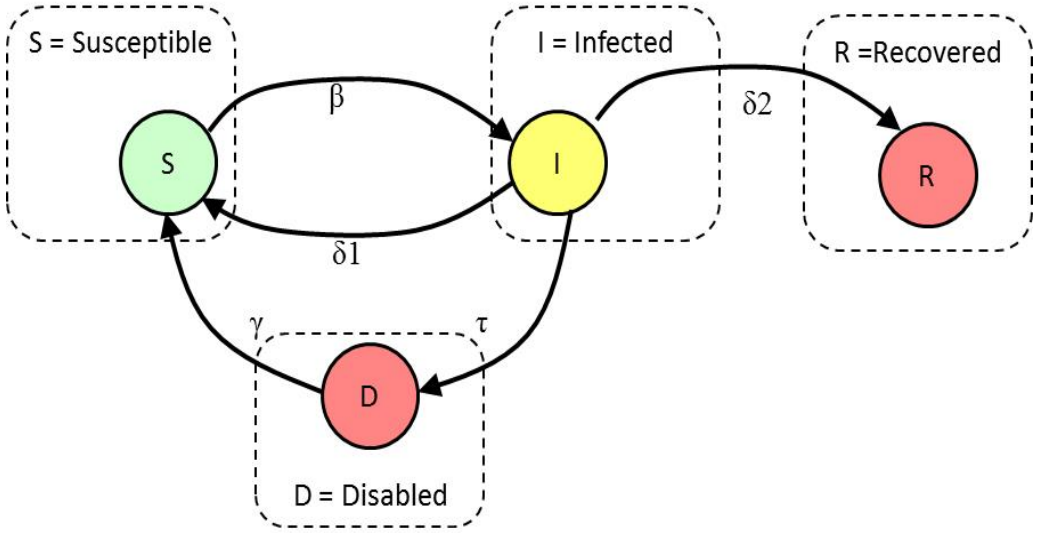
There is a strategy to maximize the impact

Most important nodes/links are attacked first, examples:

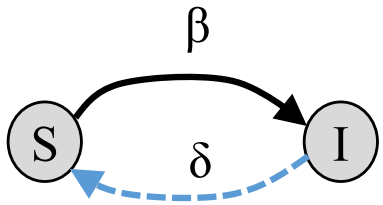
- Nodal degree
- Betweeness
- Other

Dynamic scenarios: **epidemics**

Classical models of contagion define some state (or compartment) for the individuals such as susceptible, infected and infectious (and many more!).

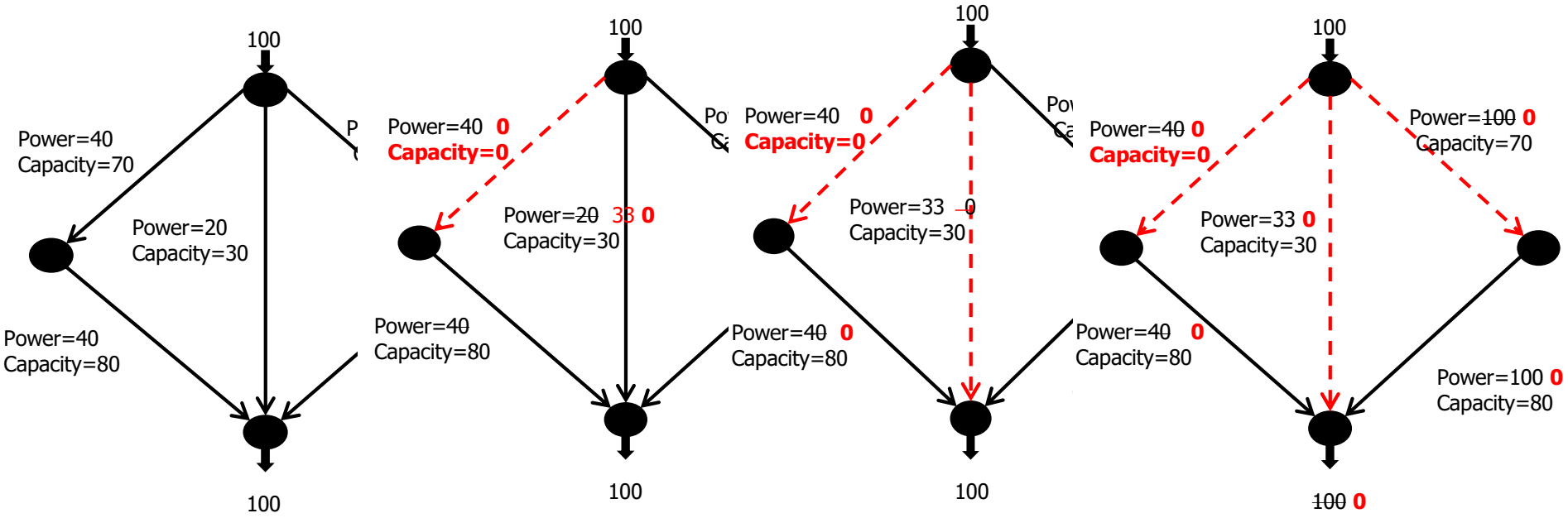


A simplified model is used in our simulator:



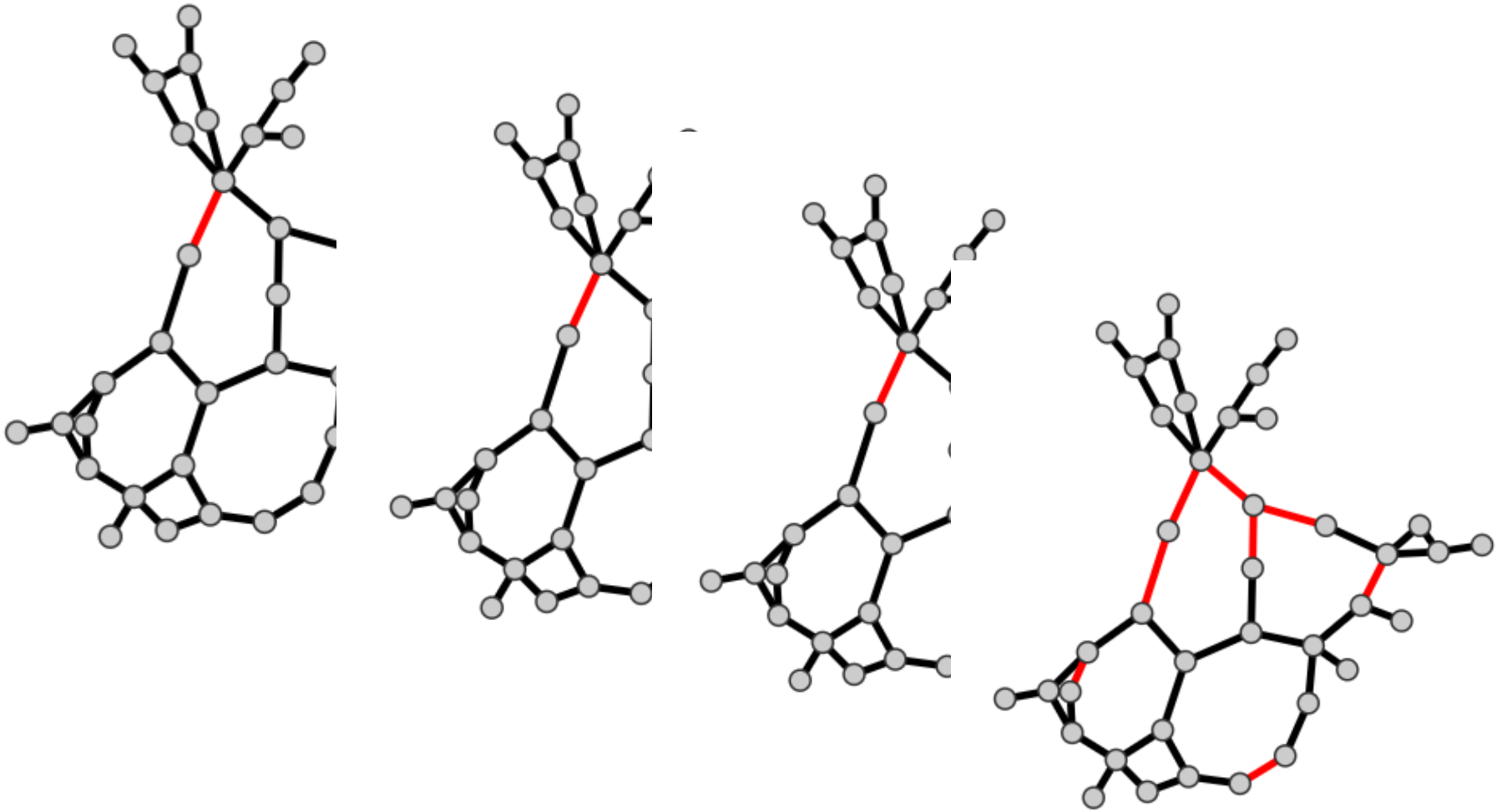
Dynamic scenarios: **cascading**

A failure that propagates in the network can be modelled using an **cascading** model.



Extra information is needed:
the capacity of the links and the power demands

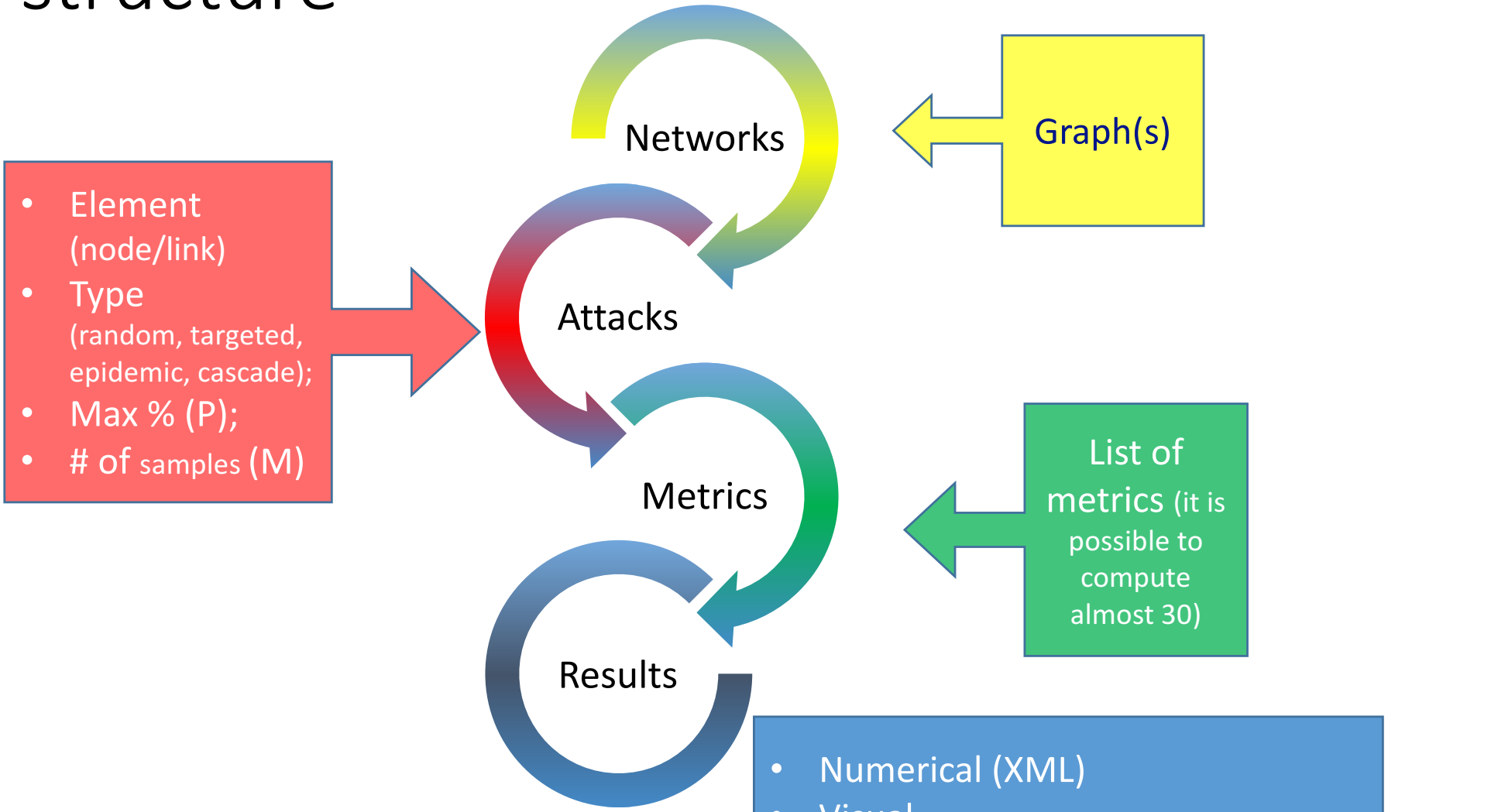
Dynamic scenarios: **cascading**



Contents

- Motivation
- The robustness concept and metrics
- Modelling massive failures
- **Robustness Computation mechanism**
  - **The Network Robustness Simulator (NRS)**
  - **Robustness surface and PCA**
- Simulation Scenario and Results
- Conclusions and future work

Network Robustness Simulator
structure

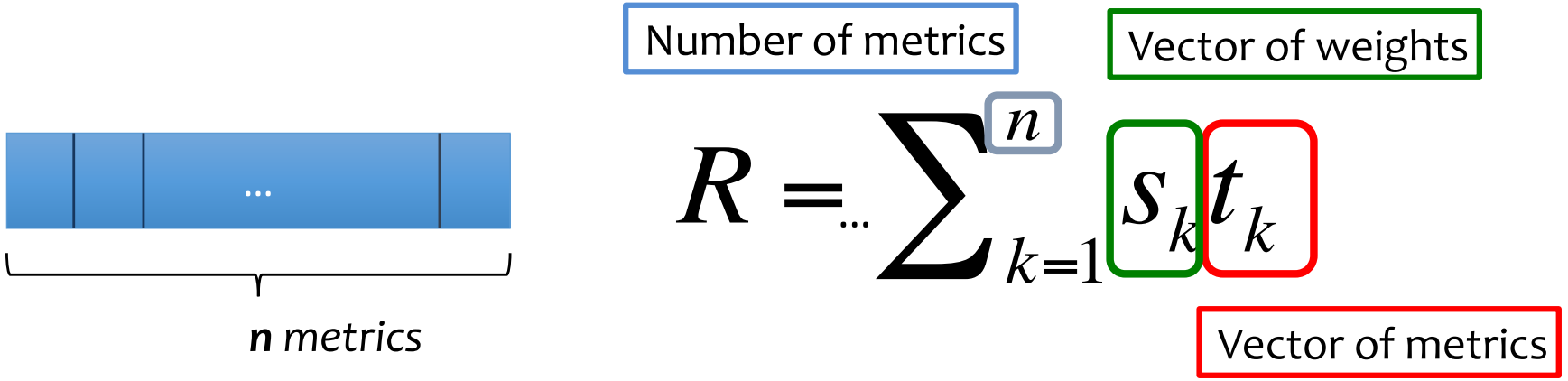


Previous work. The R value

"Can we get an unified value of robustness considering "all" metrics?"

Trajanovski et. al have proposed a framework to evaluate the robustness of complex networks, which is based on the generic metric R-value.

The R-value is denoted by:



where $\boldsymbol{s}$ and $\boldsymbol{t}$ are n × 1 weight and graph metric vectors, respectively

The R-value includes several graph metrics characterizing the network robustness.

Stojan Trajanovski, Javier Martín-Hernández, Wynand Winterbach, and Piet Van Mieghem. Robustness envelopes of networks. Journal of Complex Networks, 2013.

Robustness Surfaces. R* value

Based on R-value,

$$R = \sum_{k=1}^{n} s_k t_k$$

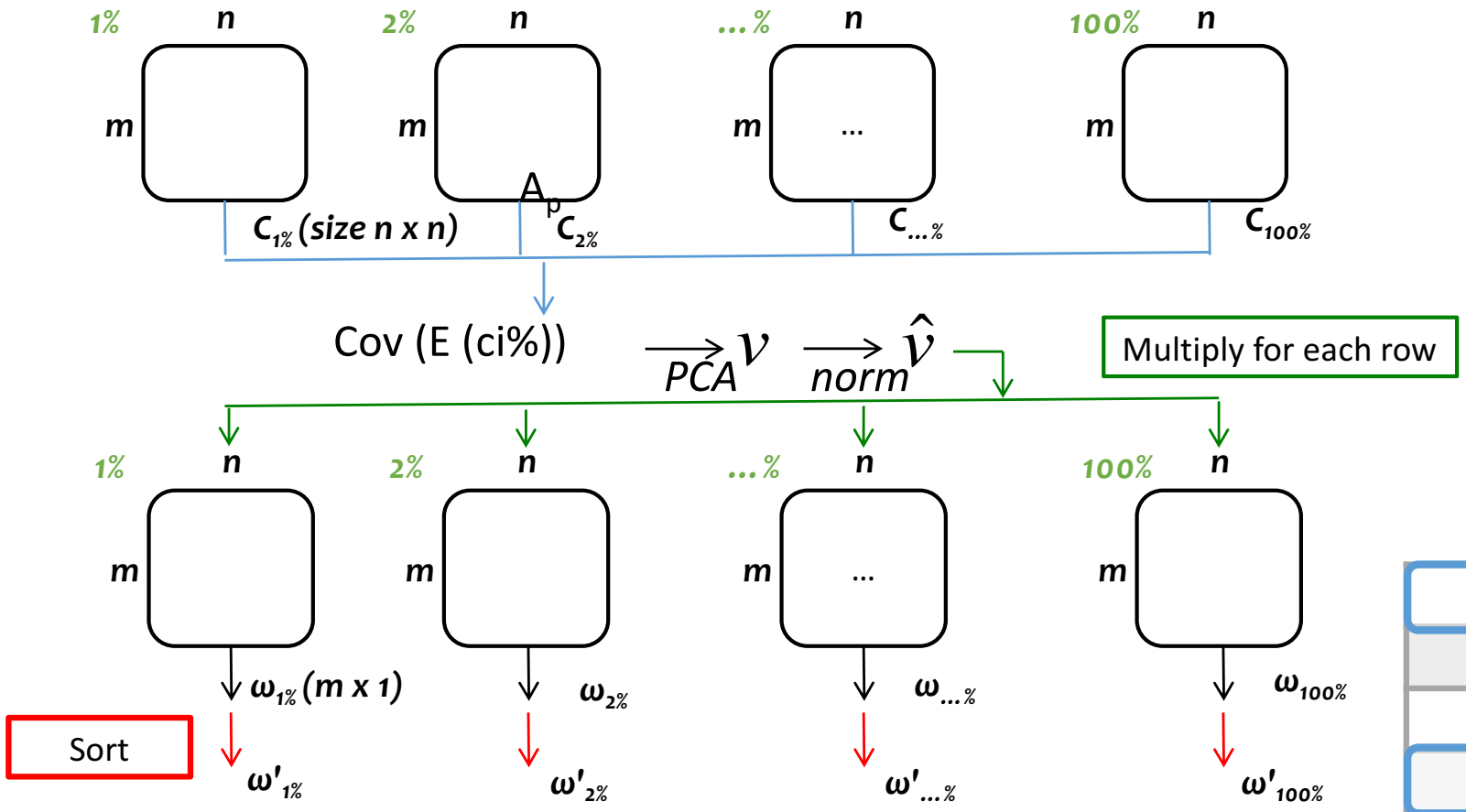
for a **dynamic** scenario we proposed the **R*-value** obtained by extracting the most informative robustness metric from the **n** computed metrics **and normalised**

$$R^*_{p,m} = \sum_{k=1}^{n} \hat{v}_k t_k$$

a normalized eigenvector

Instead of weights (s_k as for R value) a normalised eigen vector $\hat{v}_k$ is used.

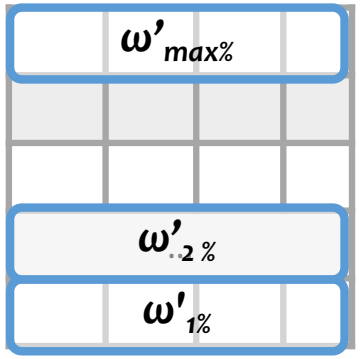
Dynamic approach
0 % to p % , m samples, n metrics



where $\omega_{1\%}=\{R^*_{1\%}, R^*_{1\%,...}, R^*_{1\%}\}$ ...

$\Omega = \{\omega'_{1\%}, \omega'_{2\%,...}, \omega'_{max\%}\}$

Ω matrix

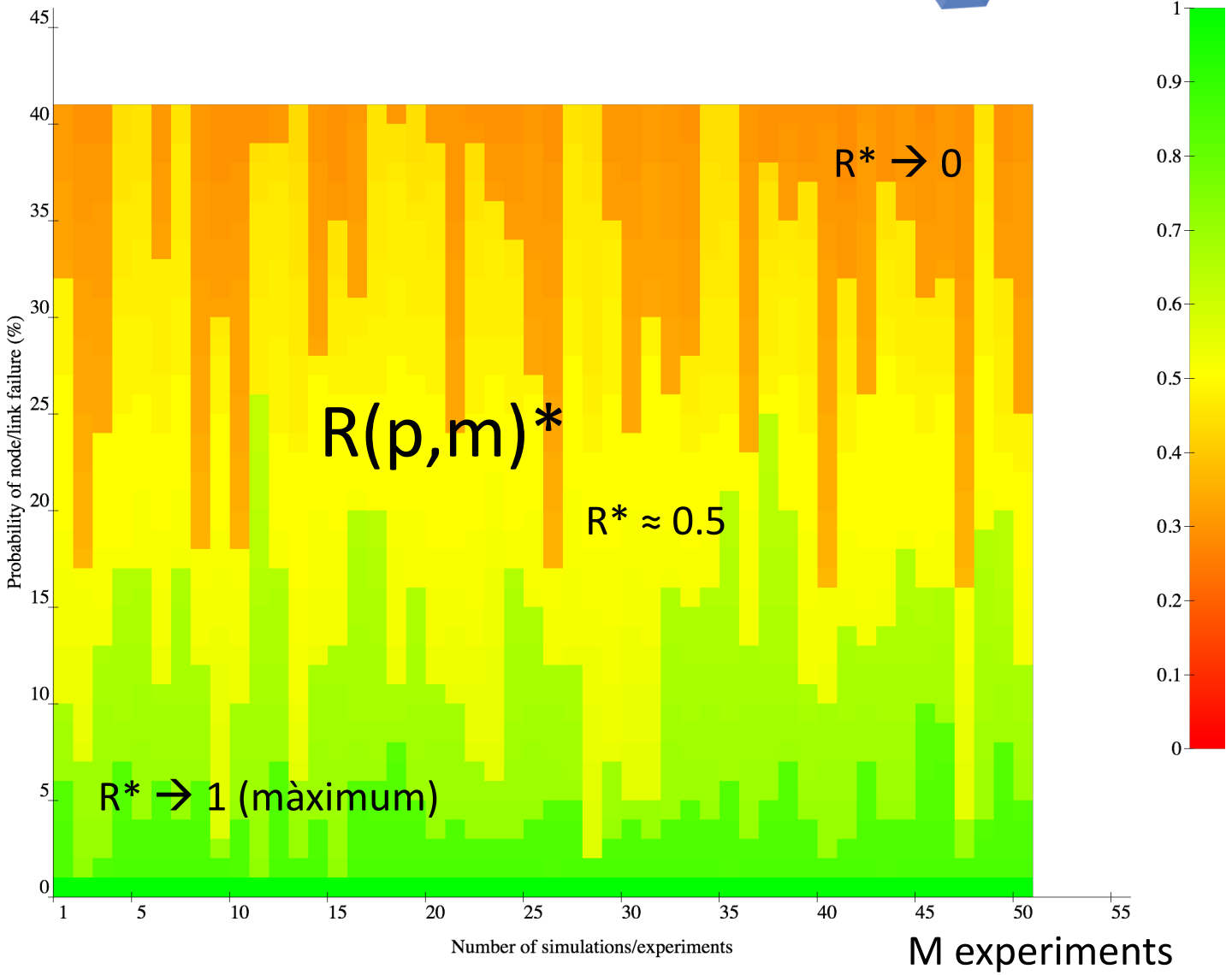


Robustness Surfaces: initial

- In the example a network is "stressesed" by removing up to **P%** elements
  - P varies 0% to 40%
  - P (40) rows are obtained.
- For a given P, **M** independent experiments are performed.
  - M varies 1 to 50
  - M columns are obtanined.

P %

p

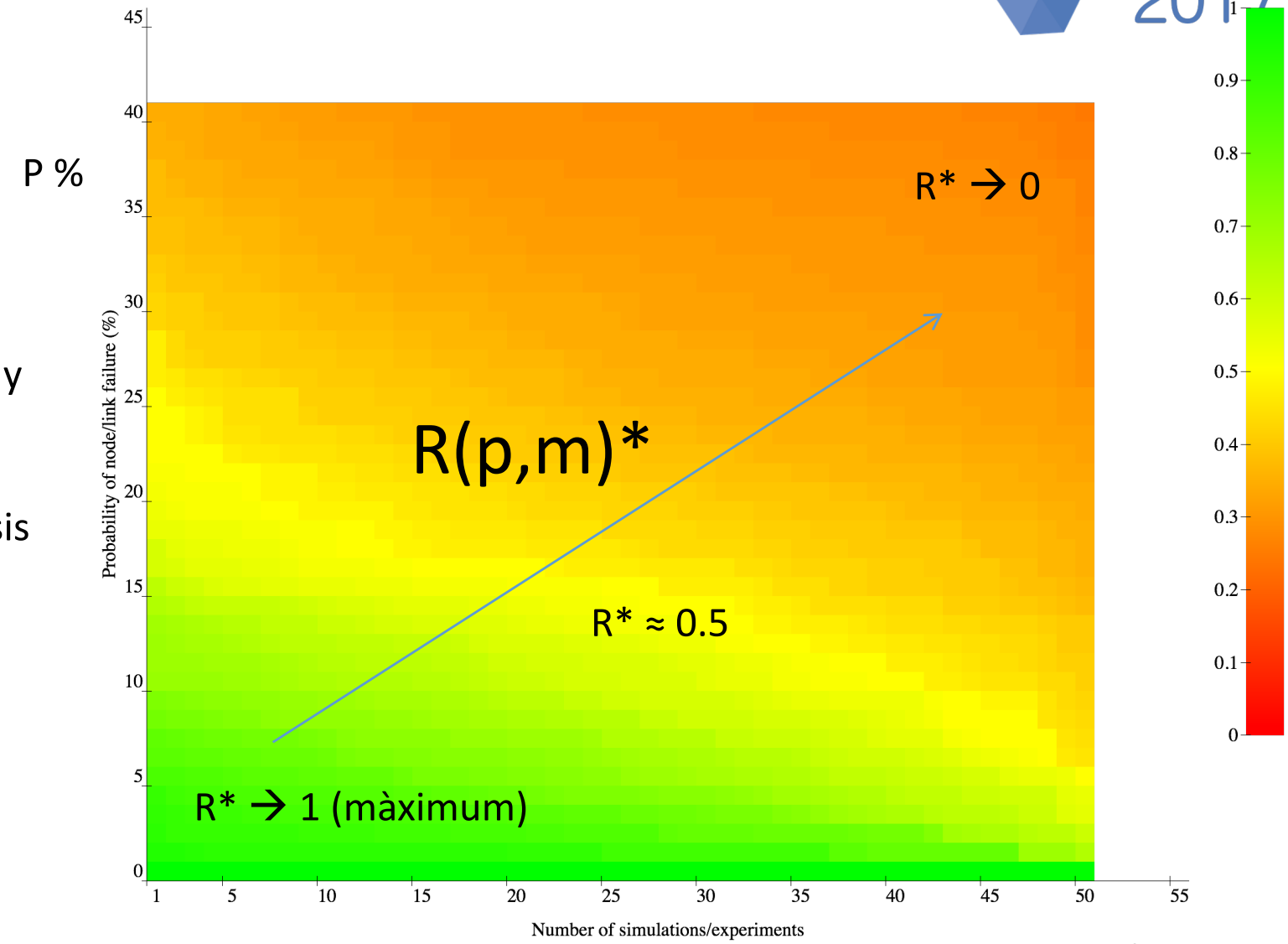


M experiments

m

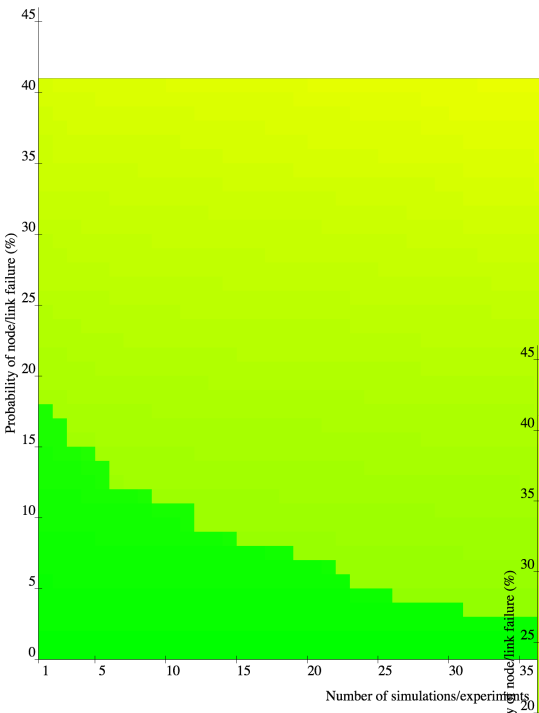
Robustness Surfaces: sorted

- As the results in columns are actually independent rows are sorted for a better **visual** analysis
- Then a Robustness surface is obtained



"Robustness surfaces of complex networks", *Manzano, M., Sahneh, F., Scoglio, C., Calle, E., & Marzo, J. L.* Scientific Reports, Nature. September 2014

Some results
Robustness surfaces



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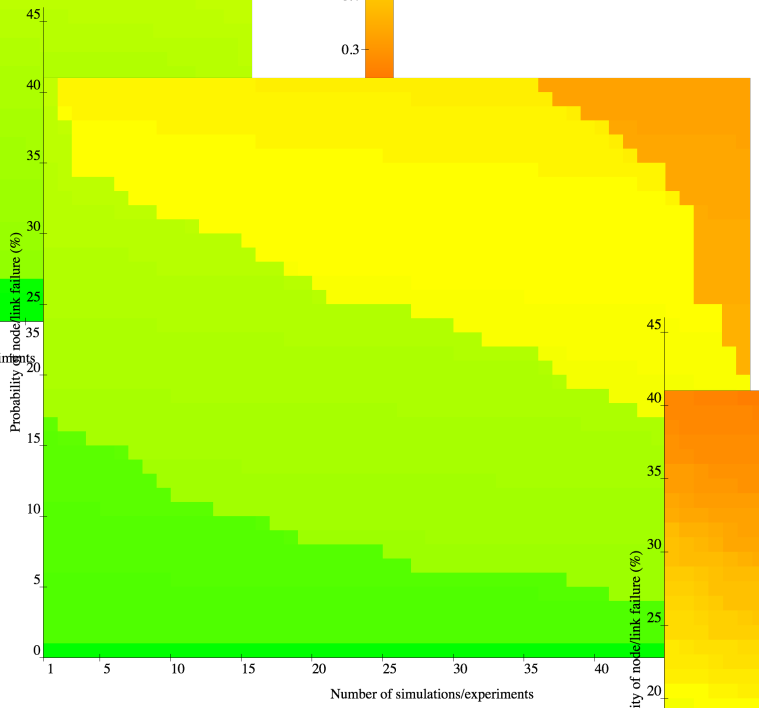
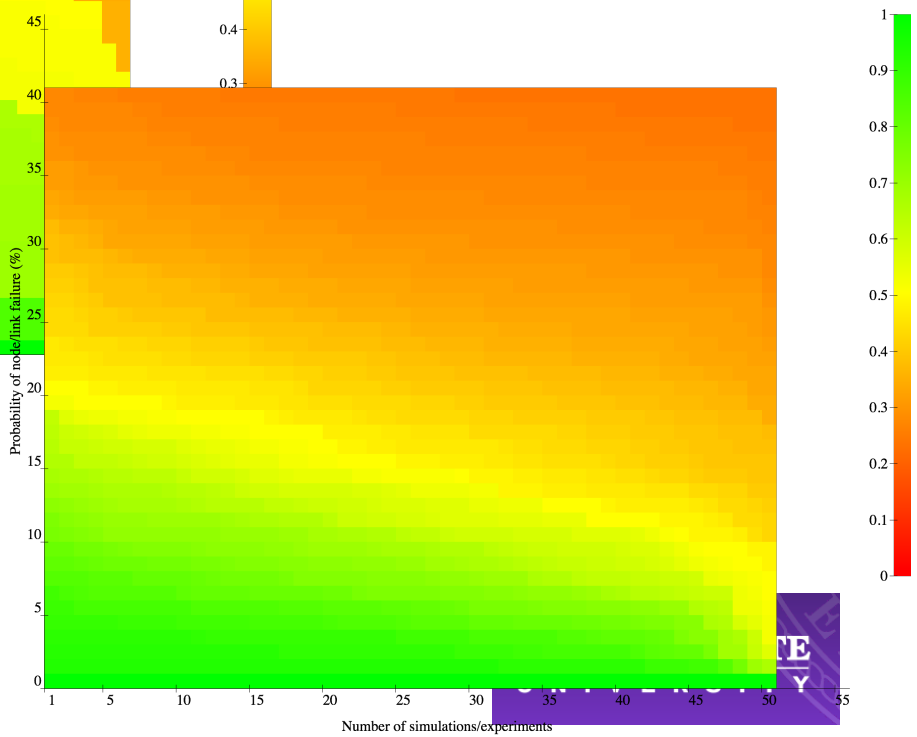


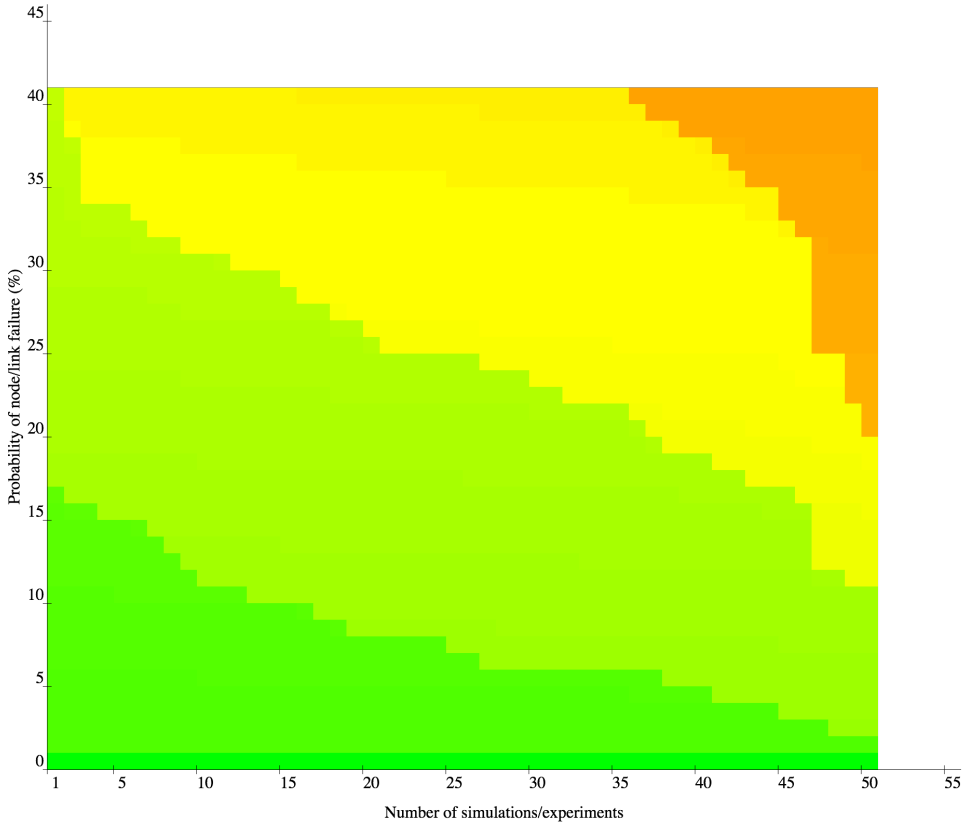
Grid

Random

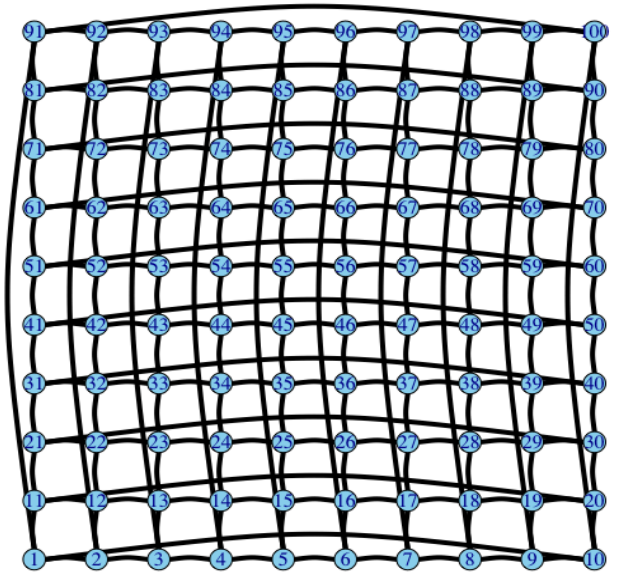


Tree

Random



Grid



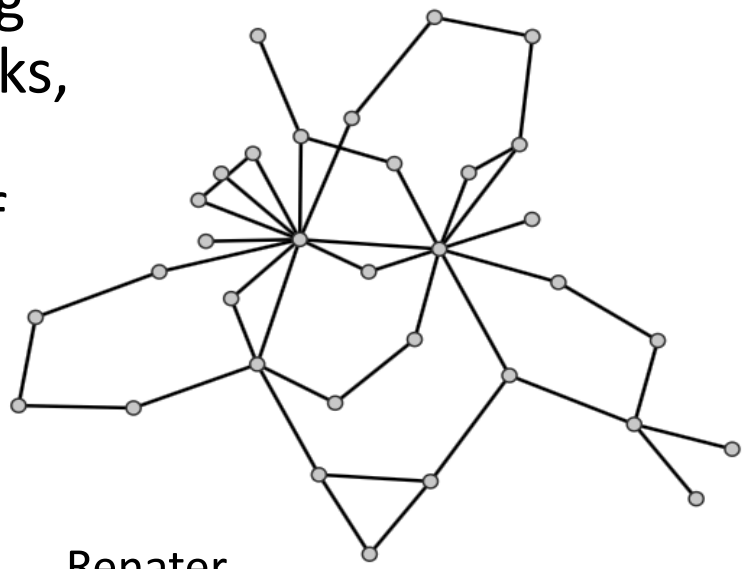
Targeted

Contents

- Motivation
- The robustness concept and metrics
- Modelling massive failures
  - Introducing Epidemic models
- Robustness Computation mechanism
  - The Network Robustness Simulator (NRS)
  - Robustness surface and PCA
- **Simulation Scenario and Results**
- Conclusions

Simulation Scenario

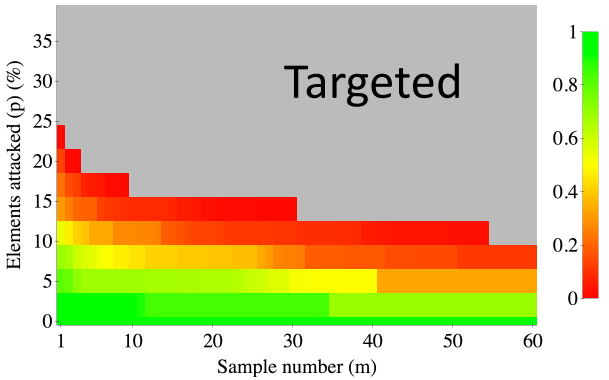
- In general, **targeted** attacks damage the most the networks, followed by random and epidemics (which damage the less).
- Explanation: epidemics always remove a node linked to the previously removed, i.e. epidemics enlarge a single “hole” meanwhile random (and indeed targeted) make independent “holes” (being the impact to the networks more severe).
- When looking for topologies showing better robustness to epidemic attacks, we found out that it was always the case where the topology has a set of connected “hubs”.

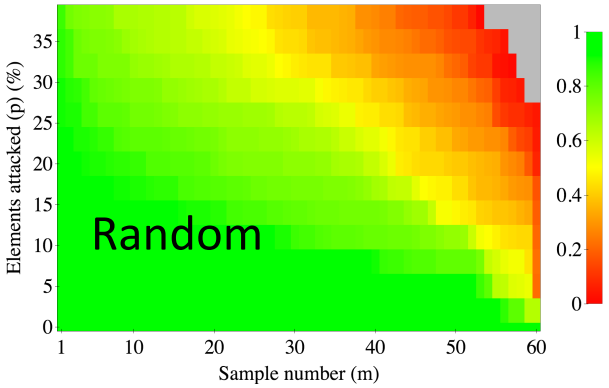


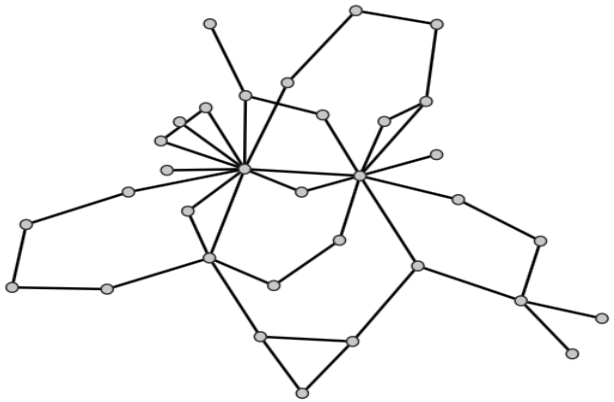
Renater

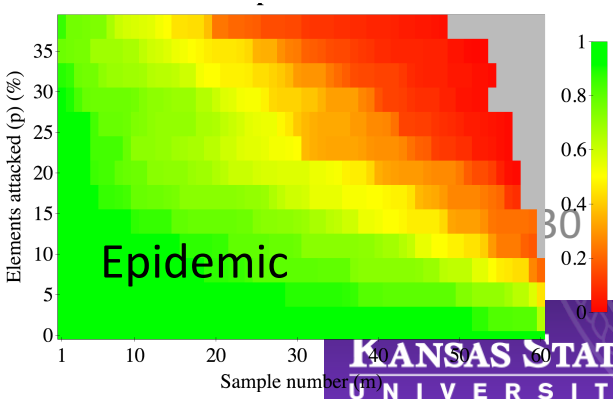
Different attacks to Renater

- The Renater network is selected.
  - It is clearly appreciated two closely interconnected hubs.
  - This structure facilitates de expansion of the epidemic model.
- For **targeted** attacks, the robustness is shaply reduced
  - Above 15% of removed elements gives values of Robustness (R^*) very close to zero
- **Epidemic** gives **smaller** robustness (more red/grey area) average of R^* is 0.55 (0,66 in the case of random)
- The robustness surface of **epidemic** shows **sharper** behavior (clear transitions) due to the fact that when reaching a hub, the damage is higher.



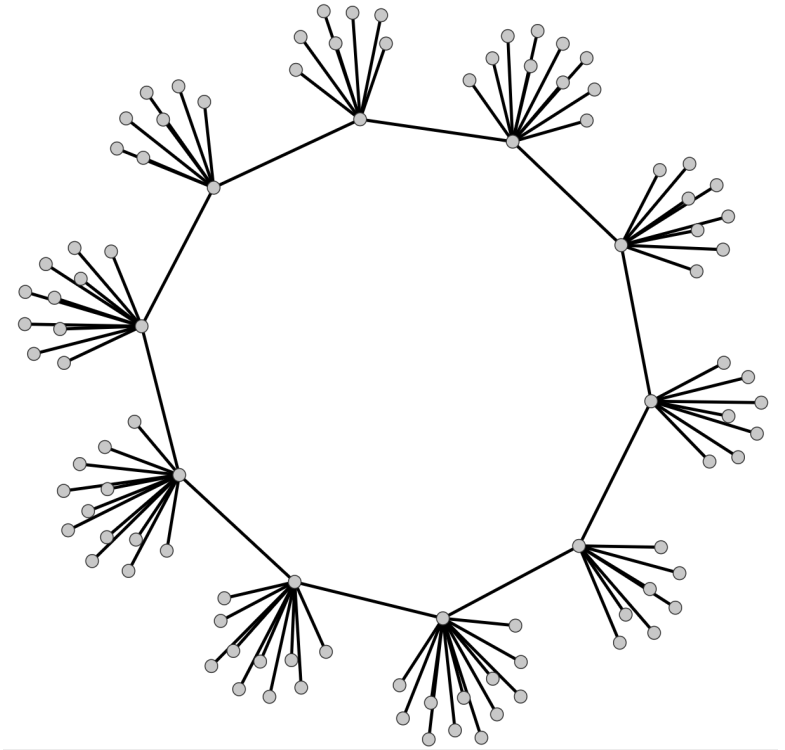






Simulation Scenario (ii)

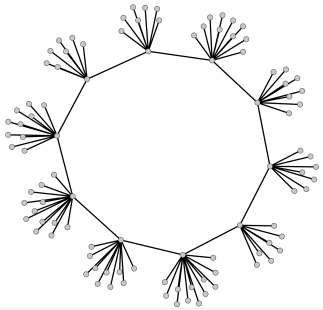
- It was studied the optimal robustness characteristic to random breakdowns for networks.
- These topologies are formed by a small group (proportional to $\sqrt{N}$)
  of well-connected hubs while the remaining nodes ($N-\sqrt{N}$) have degree equal to one (“leafs”)
  - where N is the total number of nodes.

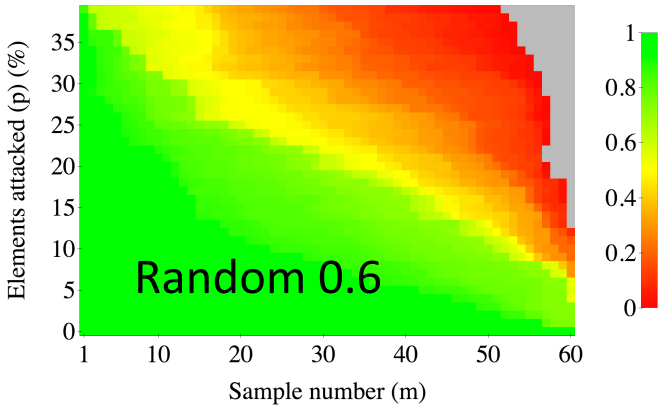


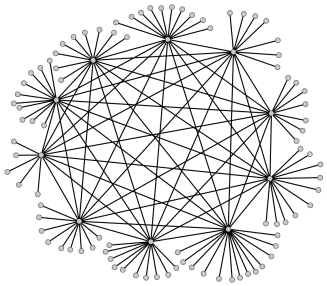
Gerald P, Sameet S, Shlomo ,H. Eugene S. “Optimization of network robustness to random breakdowns”. Physica A: Statistical Mechanics and its Applications, Volume 370, Issue 2. Elsevier. 2006.

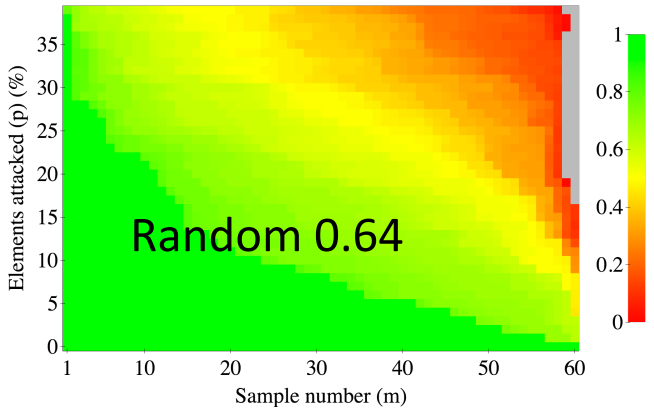
Simulation Scenario

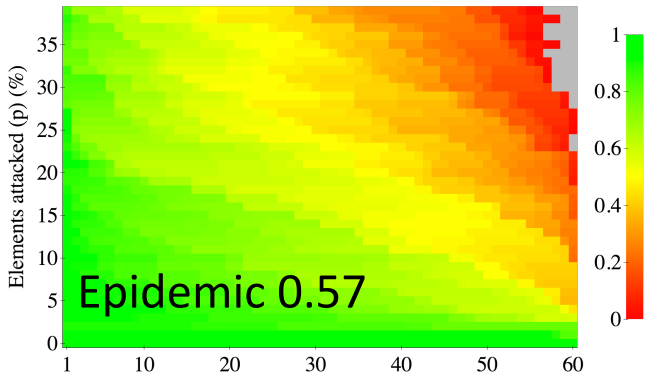
- csadvcsvs

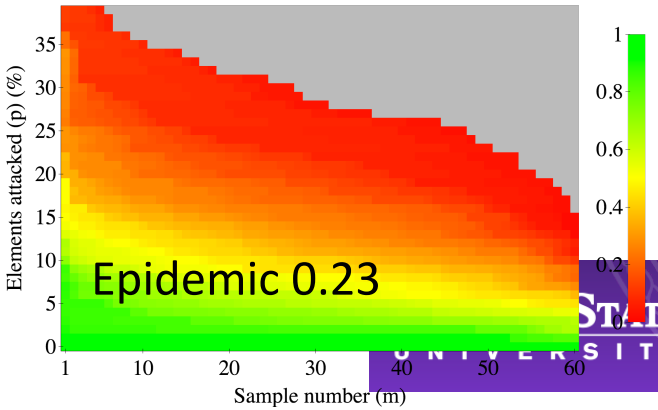












Conclusions

- A complete set of metrics are computed by extending the calculation to different percentage of failures and failure configurations (dynamic scenario)
- Principal Component Analysis (PCA) is used to extract the most significant information of a set of robustness metrics which is used to normalize R-value (obtaining R*-values) therefore the robustness of different networks can be easily analized and compared
- Drawing the robustness surface, a novel framework is provided to visually assess the network robustness variability

Future work

- Expanding the simulator:
  - Adding new metrics, in particular functional ones
  - New attack strategies/models
- Interdependent networks
  - New interdependency models
  - Expanding visualization tool to cope with (at the moment just two networks)
- Working in a new responsive interface for the Network Robustness Simulator
- Current version allows a basic parallelization. As computations are in essence quite independent each other, we think that an study of this factor would increase the speed of calculations increasing scalability.

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