Criticality of the European Electricity Grid Network

MANMADE ***EU NEST FUNDING***

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Interdependent complex structures: MANMADE proposal

- The scope of the project concerns the network of networks that comprise Europe's critical infrastructure; concentrating primarily on energy supply, emergency response systems and subsidiary key infrastructures.
- The aim of the project is to assemble, develop and apply mathematical methods to analyse large, man-made multi-element infrastructure systems that exhibit, so-called, complex behaviour.

Study generic network behaviour:

- instabilities and collapse: both structural (catastrophic failure of network components), functional (electricity grid blackouts, supply chain),
- volatility and memory (spot electricity pricing),
- feedback (influence on congestion in networks)
- inter-network coupling (e.g. vulnerability of interconnected networks to unexpected failures)

MANMADE Project Partners

Participant organisation name
Queen Mary, University of London
JRC-IPSC Ispra, Italy
Collegium Budapest
Macedonian Academy of Sciences and Arts
Universita Carlo Cattaneo, LIUC

WORK PACKAGE SCHEDULE

WORK PACKAGE TITLE	LEAD CENTRE	Person -mths	Start month	End month
Project Management	QMUL	23	1	36
Network Collation	JRC	45	1	36
Mathematical Methods	QMUL	108	1	36
Electricity Networks	COLB	58	1	36
Dynamics of supply-chain and market volatility of networks	LIUC	55	1	36
Vulnerability of interconnected networks	MASA	70	1	36
TOTAL		359		

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Important structures can be modelled as networks

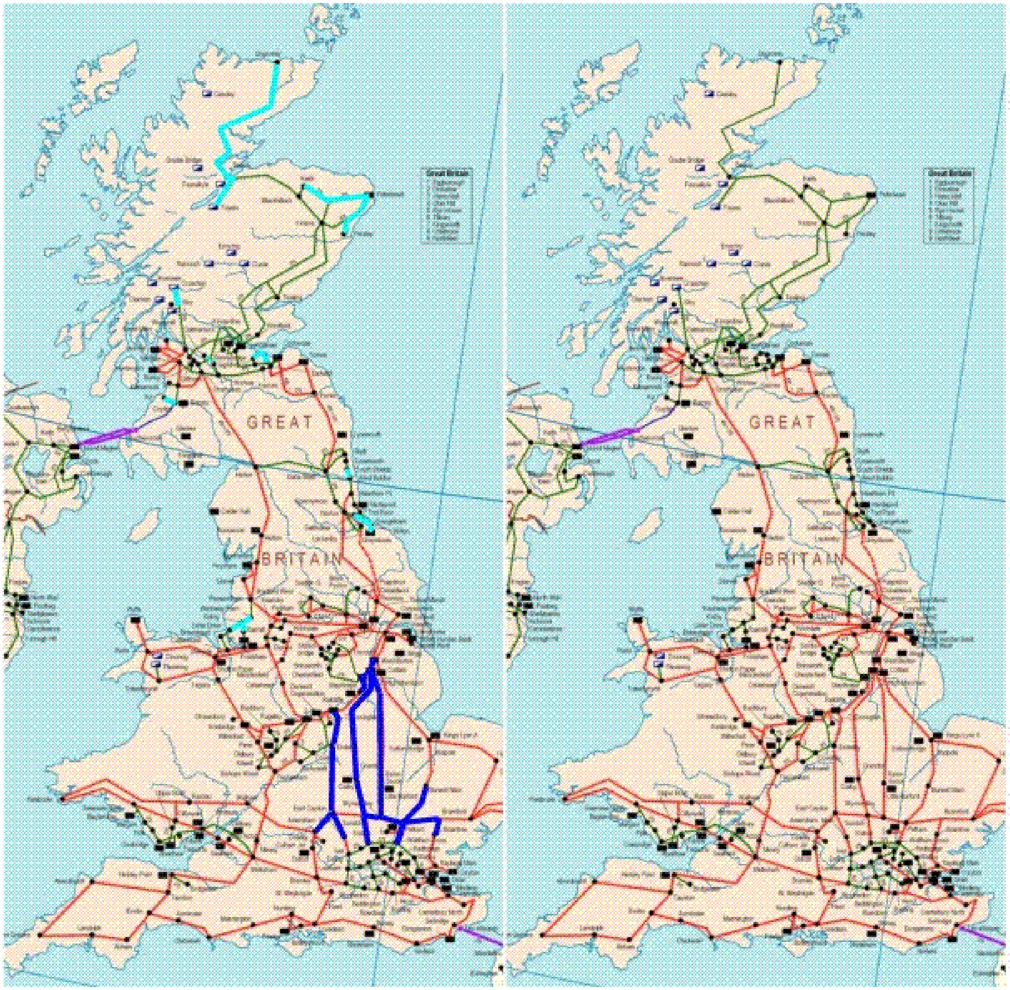
- Social organizations (….good and bad)
- Energy
- Transport
- Communication
- ……networks of networks

What are the most useful analytical tools to handle them?

Analysis of Networked Systems: Energy Distribution

- Energy distribution systems are large, interconnected, networks coupled by non-trivial dependencies.
- One of the tasks is to analyse energy networks at the macro-scale.
  - Large networks are not easily tractable with standard causal mathematical methods➔➔Graph theoretic methods.
  - Networks can be defined in terms of the topological properties of their graphs.
  - What can be said of their failure rates?
  - What can be said of the vulnerability of the whole?

UK primary power grid



Mathematical methods to diagnose status of networked systems using:

<u>Statistical analysis:</u> insight as to how 'stressed' the system is: e.g. are blackout trends in Europe consistent with critically organised systems?

Statistical distribution of blackouts (Gaussian vs. Power laws imply widely differing expectancies for widespread failures).

- Does system have 'memory' of past events (Hurst Coefficient).

<u>Topological features</u> define the sensitivity of network links to different failure distributions.

Is network connectivity randomly distributed (insensitive to 'attack' strategy), or scale-free (normally v. robust, but, highly sensitive to selective attacks)?If scale-free: where are the weakest corridors (vulnerability analysis)?

Foundations of approach: Albert et al. 2000, Barabasi *et al.* , 1999), EPRI/DOE Complex Interactive Networks Program (Massoud 2004), Carreras et al .2004

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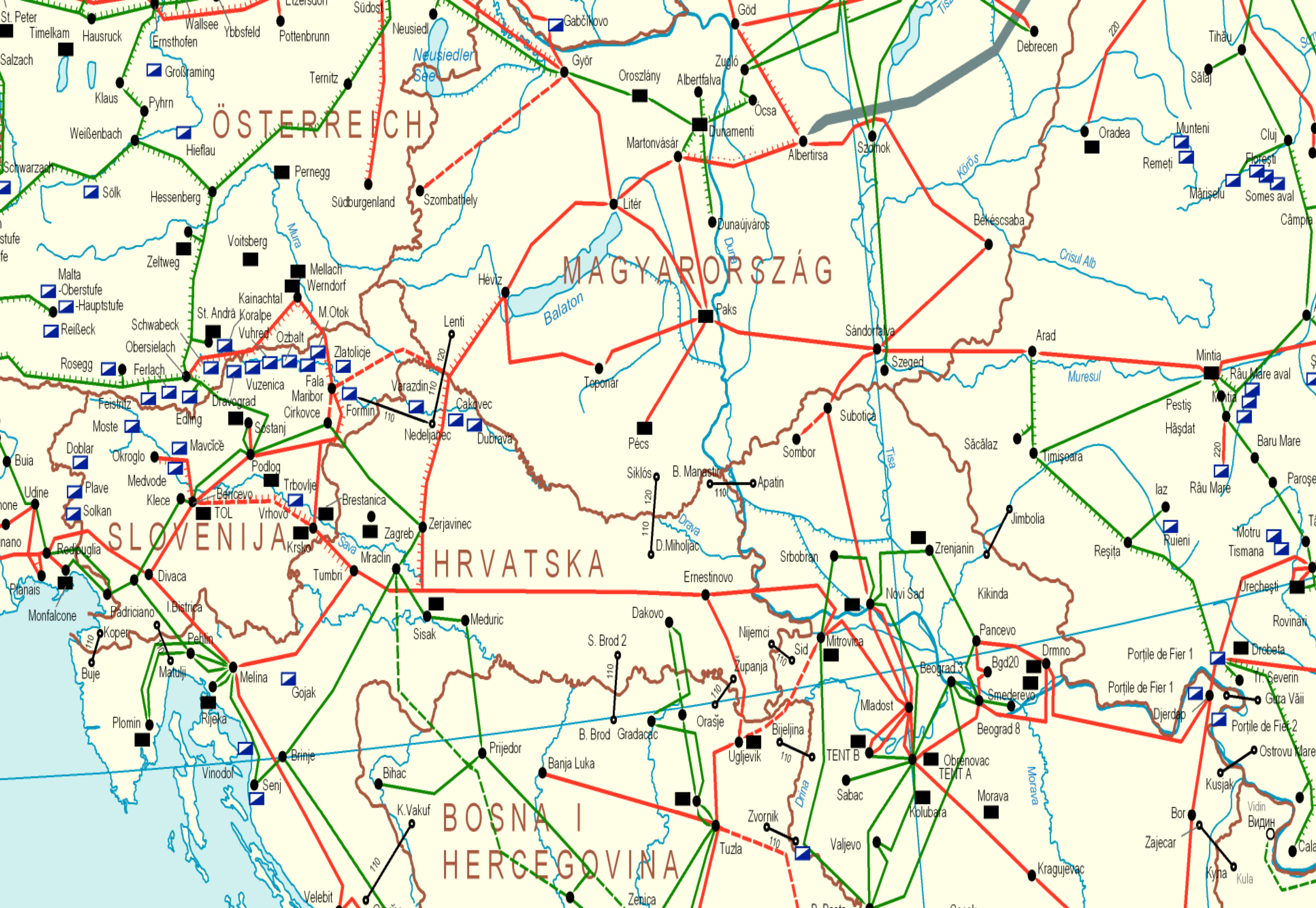

St. Peter
Timelkam
Hausruck
Wallsee
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Südost
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Gabčíkovo
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Debrecen
Tihău
Salzach
Ernsthofen
Großraming
Neusiedler See
Győr
Oroszlány
Zugló
Albertfalva
Ócsa
Sălaj
Ternitz
Klaus
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ÖSTERREICH
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Albertirsa
Szolnok
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Novi Sad
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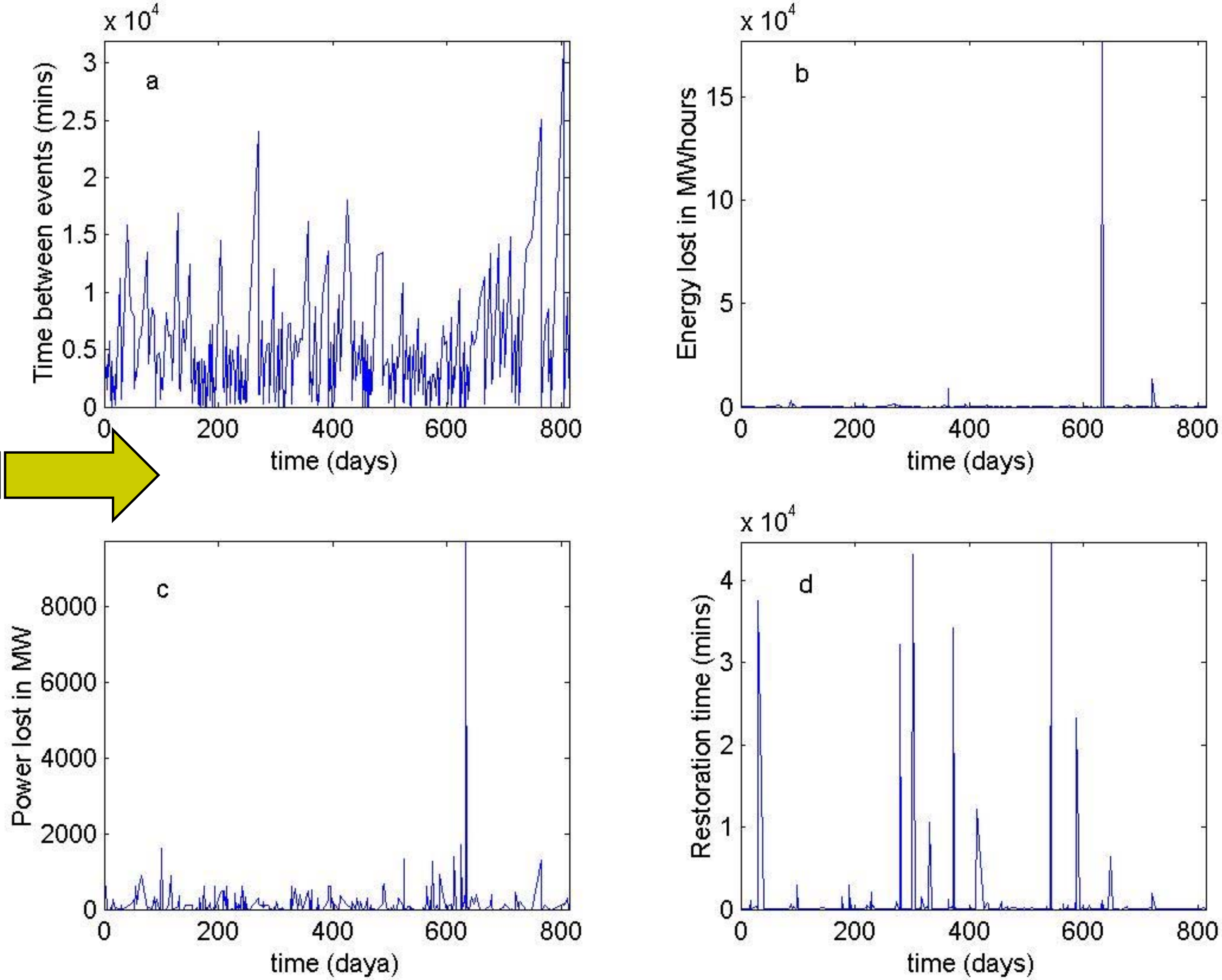
Kragujevac

Blackout Analysis

- To analyse the qualitative characteristics of power disruptions from a large synchronously-connected electricity grid. (Following from Carreras et al. *Evidence for self-organized criticality in a time-series of electric power system blackouts*, IEEE Trans. 2004)
  - Are European electricity grids critically organised systems?
  - What are the expectations of large blackouts?
  - Are events correlated or random?

Time series of UCTE disruption parameters:

340 disruption events over 28 months from 01/2002 till 03/2004



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Diagnostic parameters calculated from time series

- Hurst exponent:
  - A means of detecting long-range dependence in the presence of noise.
- Cumulative frequency distribution:
  - The tail of the cumulative frequency distribution provides information on the rate of decay of perturbations as a function of the blackout size.

Conclusions: Hurst Coefficient

- Waiting time between disruptions is persistent: time between events in the past affects the waiting time in the future at all time scales.
- For short time-scales (from a few days up to six months) magnitude of events in the past affects future magnitudes.
- For longer time-scales (years) magnitude of events is volatile: big events will be followed by small ones and vice versa. Similarity with electricity spot price volatility.
- Restoration times (duration of blackout) seem to be independent of each other.

Conclusions: Cumulative frequency

- Large events are more probable than expected for a random distribution (e.g. Italian blackout of 9/2003 exceeded power law of all prior events, followed by events in Luxembourg and Greece in 2004)
- Interdependencies: Implications for other critical infrastructures if failure rates are not Poisson distributed?

Case study of error and attack tolerance of a sector of the European electricity HV grid

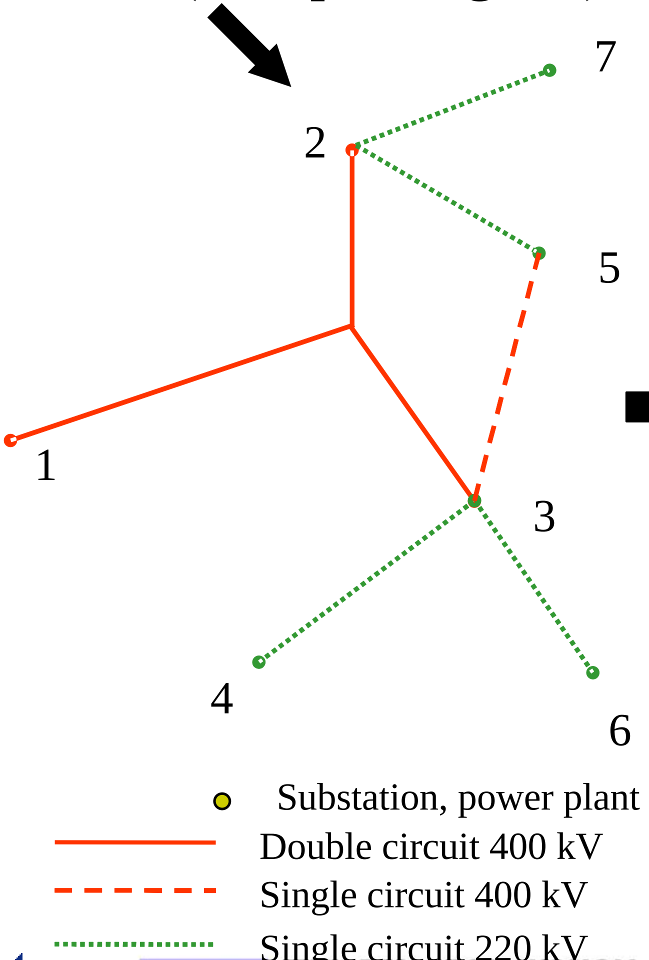
Study fragmentation of networks as a function of failure scenarios such as:

- Random malfunctions.
- Malfunction of most-connected nodes.
- Malfunction of ‘busiest’ nodes/lines
  - How to identify potentially ‘busy’ nodes and lines from a large network (assume poor knowledge of flow data).

….first, we need to convert the grid map into a network graph…

Conversion of HV grid map into a weighted graph

Grid (interpret legend)

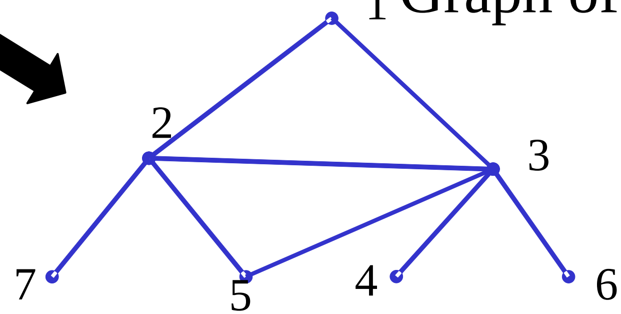


Connectivity matrix

	1	2	3	4	5	6	7
1		400	400				
2	400		400		220		220
3	400	400		220	800	220	
4			220				
5		220	800				
6			220				
7		220					

Modes

Graph of network



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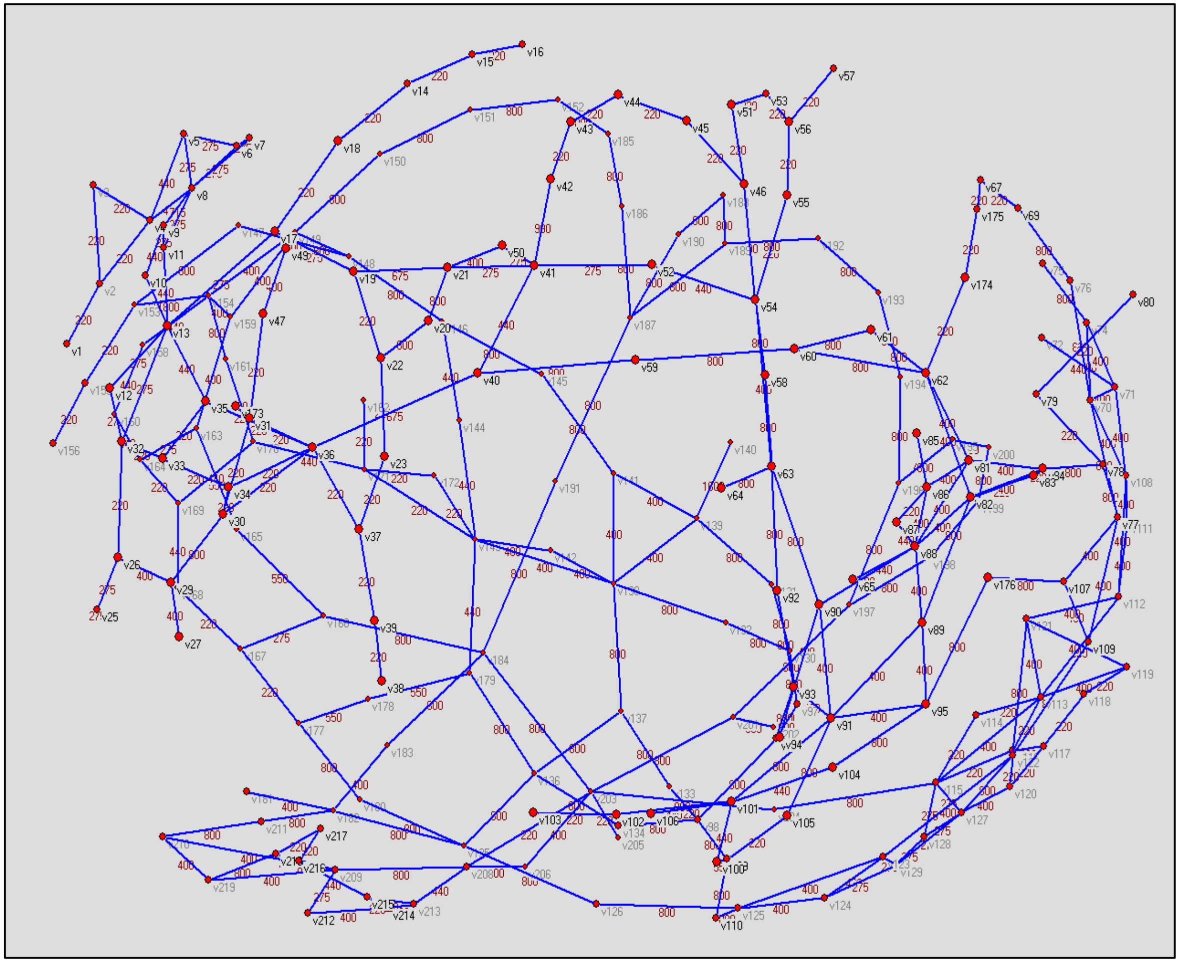
The weighted graph representation of the electricity grid sector chosen for analysis

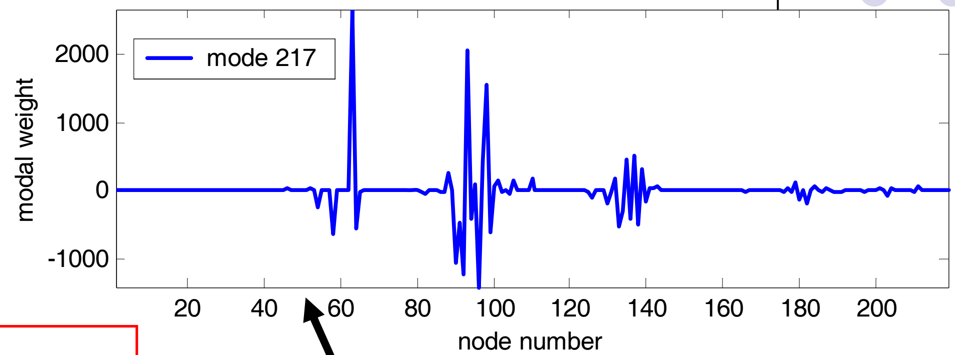


219 vertices
309 HV lines
>50 million clients

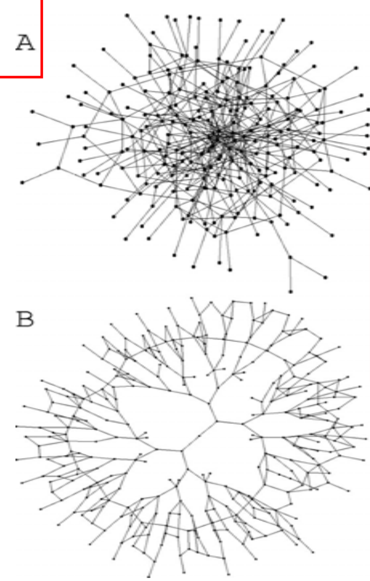
219 Modes of flux flow

*Visualization using **Pajek** network analysis program.

<u>Connectivity matrix</u>: can be used to study magnitude and distribution of potential flows (<u>modal analysis</u>)➔ high flux corridors.



Example: Mode 217 connects node 63 strongly to nodes 93,96 and 98. What happens if node 63 is eliminated? Along which lines does mode flow through?



Topological properties of graphs (diameter, distance, cluster size) can be measured as a function of node/line elimination.

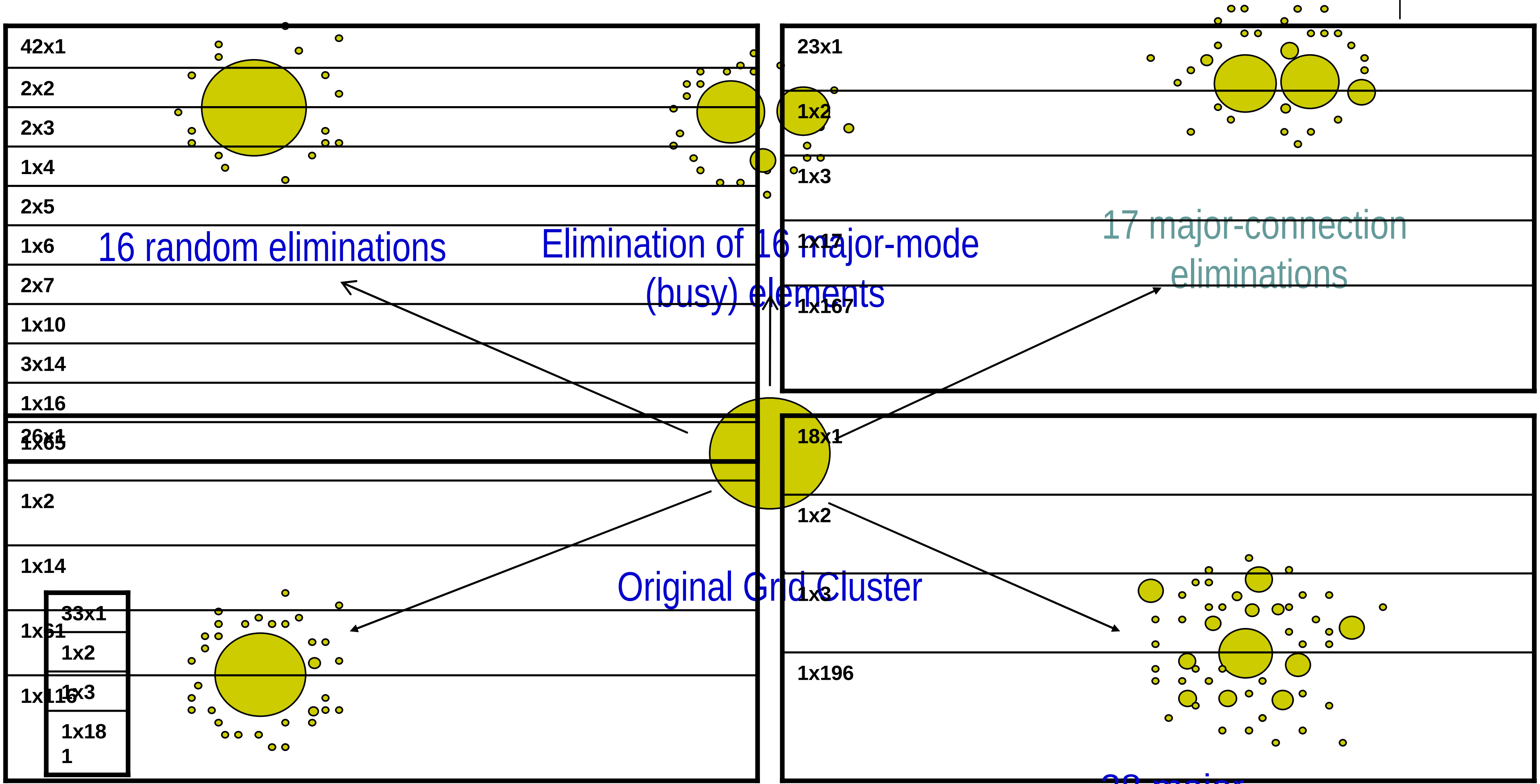
A and B are clearly different.
How? How much, and how does it affect vulnerability?

The graph representation of potential transmission modes.

Potential flow Intensity represented in grey-scale

Size of vertex proportional to modal weighting.

Response of Network to selective and random strategies

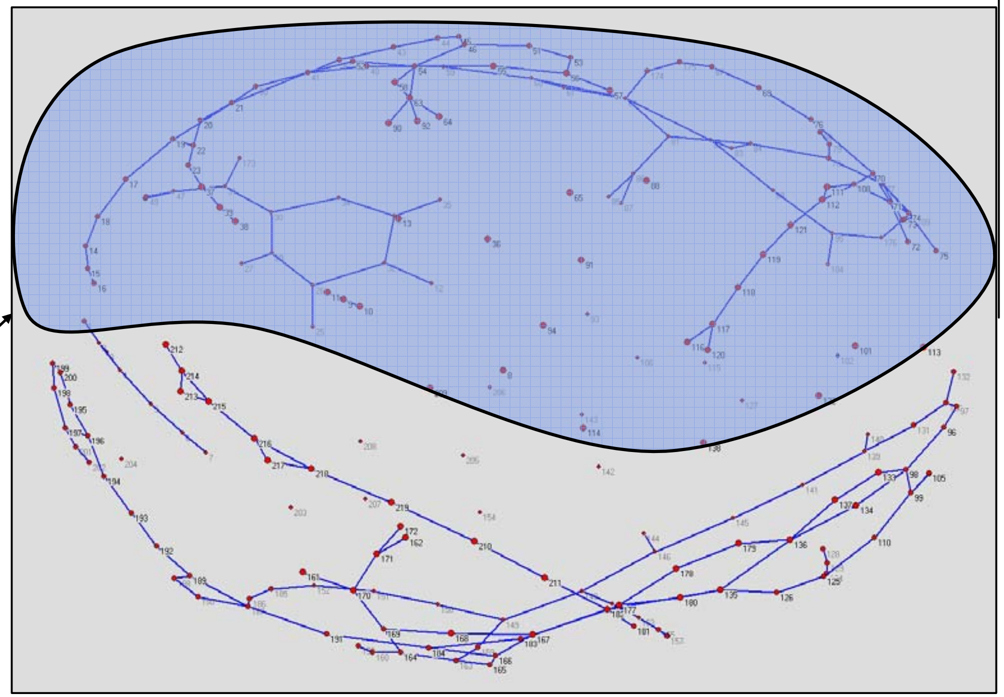


28 random eliminations

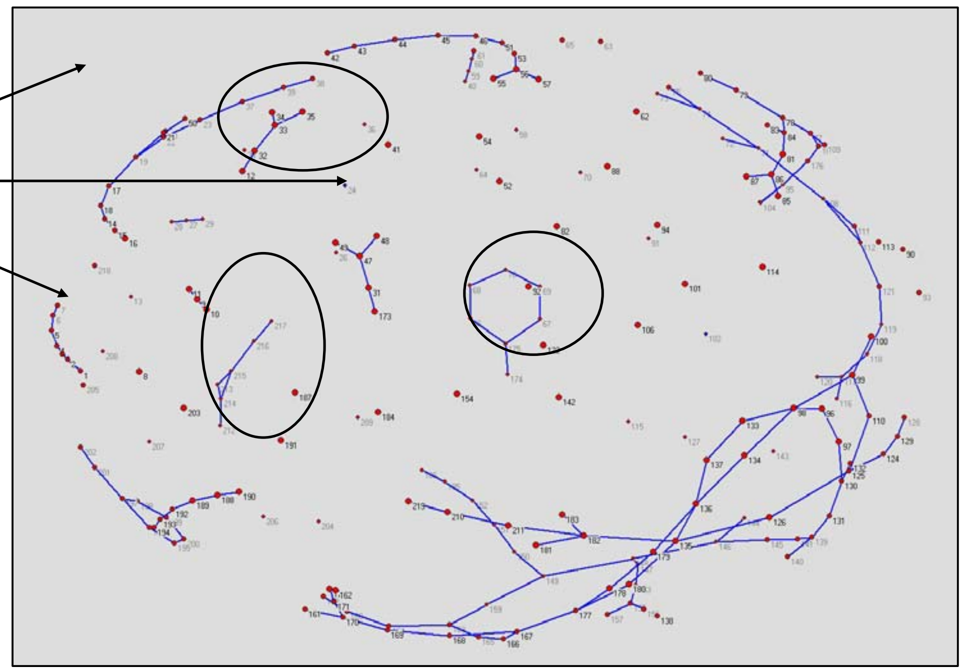
28 major-
connection
eliminations

Elimination of nodes/lines results in network partitions. The network may break up into blackout islands.

A main cluster partition



Multiple partitions



The optimal partitioning ‘strategy’ depends on the topology of the network….strategies may be calculated (malicious) or imposed by nature (seismic, wind/snow storm..).

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Problems to be addressed

HV grid network conforms to scale-free type.

- Resilient to random error failures.
- Susceptible to concerted attacks or chance errors in key highly connected nodes.

Fragmentation is fast when highly-connected nodes fail.

- Highly-connected nodes are widely distributed→ high-level strategy or extreme widespread natural event required to damage a substantial number in one go.

'Busy', high flow, corridors are not necessarily the most connected, but their elimination can fragment the system just as fast.

- High flow corridors are closely packed→easier to target?→ natural hazard event does have to span wide geography.

Next steps, problems…

- European HV grid consists of 1000’s of nodes and lines
  - How to compile information? (no single repository is available in digital format for all of Europe)
- Extend analysis to other energy networks (gas and oil, distribution)… and then
- Develop network interdependency and coupling terms
  - **Time-scale dependencies**
  - **Operational dependencies**
- Dynamical complexity (modelling non-linear processes at nodes requires influence models)
- Node diversity (substations, power plants..)
- Network evolution over time: new connections, (e.g. interconnection of UCTE to IPS/UPS, offshore wind energy?)