Case studies about electricity grid at risk of random damages

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Science for Peace and Security (2024)
Energy infrastructure resilience in response to war and other hazards
Advanced Research Workshop (ARW) supported by NATO

POLAND, Rzeszów, 23.09.2024

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Presentation plan

1. Introduction
2. Research conducted and results obtained
3. Current research
4. Source data
5. Visualization
6. Simulations and results
7. Summary

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Previous research

1. Extracting data from the PGE.
2. Bringing the data into graph form.
3. Analyzing graph properties in software packages:
    a) Gephi,
    b) Network Workbench,
    c) NetworkX.
4. Development of the results of the performed analyses.

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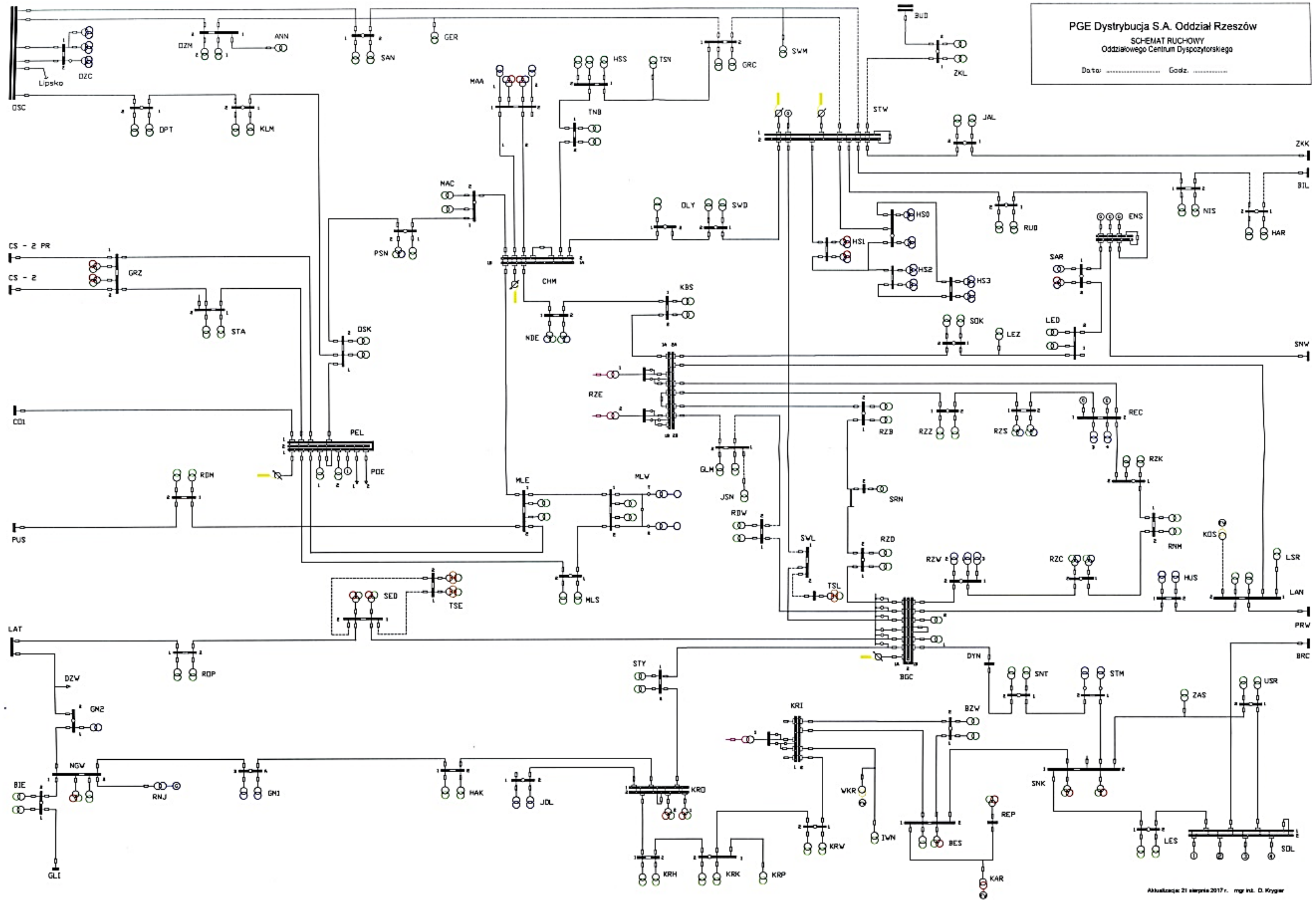
Previous research

Visualization of the logical and topological network of actual electrical connections in the PLANS package.



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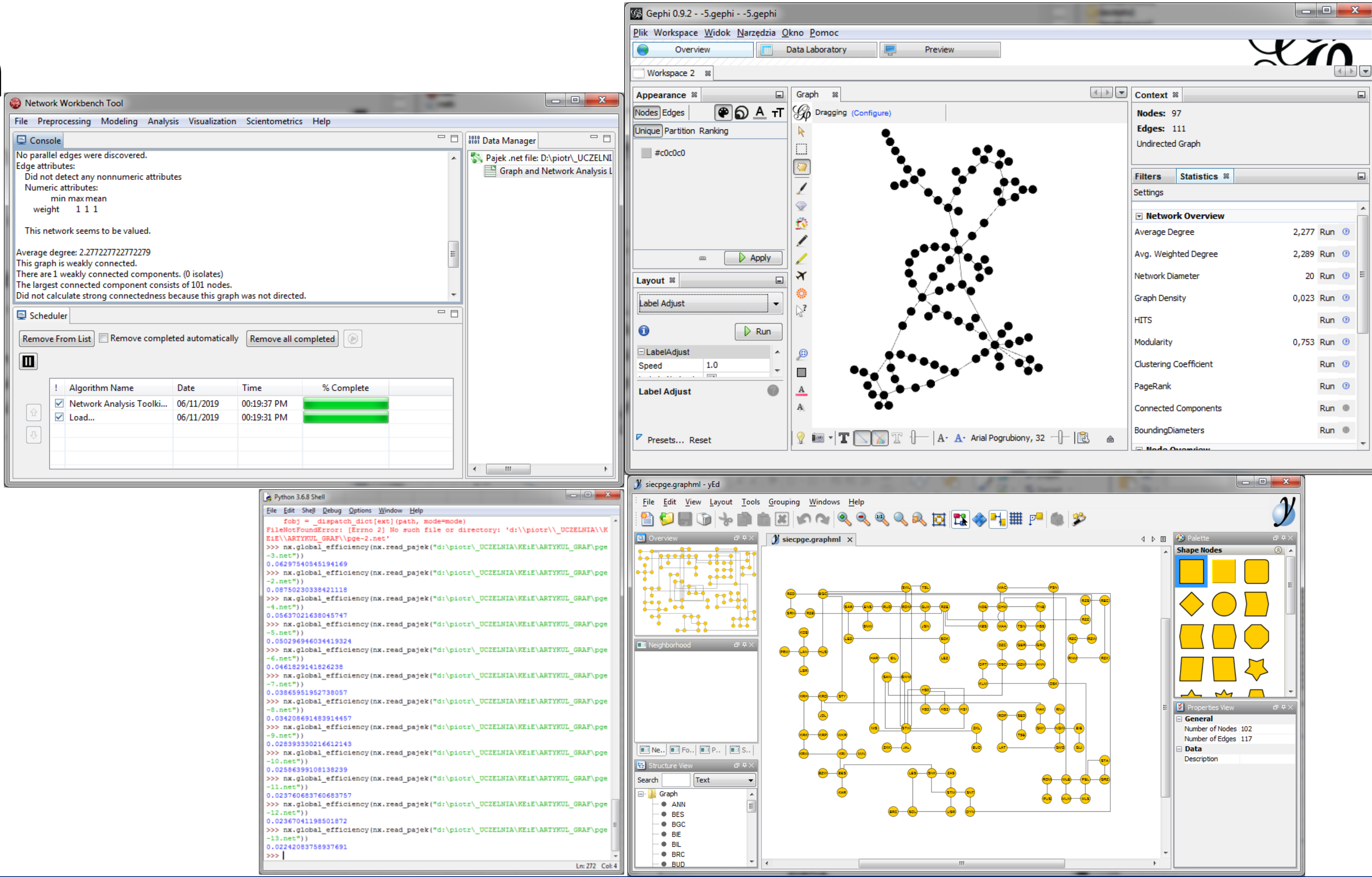
Previous research

Creating a graph of physical connections

Calculating characteristic parameters



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Previous research

Characteristic parameters of this type of graphs

1. **Average vertex degree** - the number of edges directly associated with a given vertex in the graph, determining its connections to other nodes.
2. **The number of connected components** - indicates how many parts the graph has decomposed into after removing the vertices.
3. **Graph diameter** - the longest path between two vertices in a graph, measured in the number of edges.
4. **Clustering** - a measure of how much the vertices in a graph group into clusters or clusters.
5. **Graph efficiency** - a measure of how efficiently information or influence can spread through a graph, taking into account both direct and indirect connections between vertices.
6. **Graph density** - the ratio of the number of existing edges to the number of all possible edges in the graph.
7. **Path length in a graph** - the number of edges on the shortest path between two vertices.

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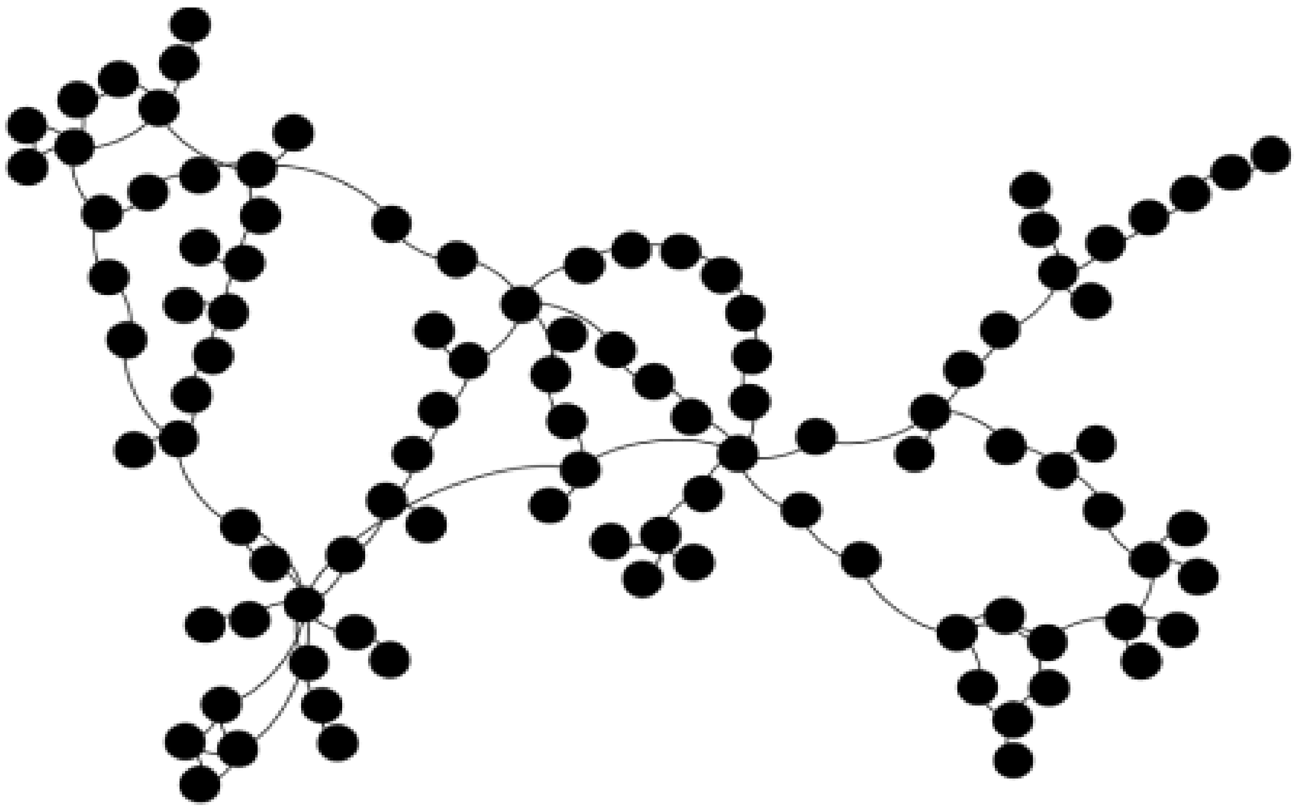
Previous research

Number of nodes in the graph	102
Number of edges in the graph	116
The average node degree	2.275
Graph density	0.023
Local graph efficiency	0.081
Average graph efficiency	0.182
Average clustering coefficient	0.099
Average path lenght	7.661
Graph diameter	20.000



Original form of the graph before the simulation procedure

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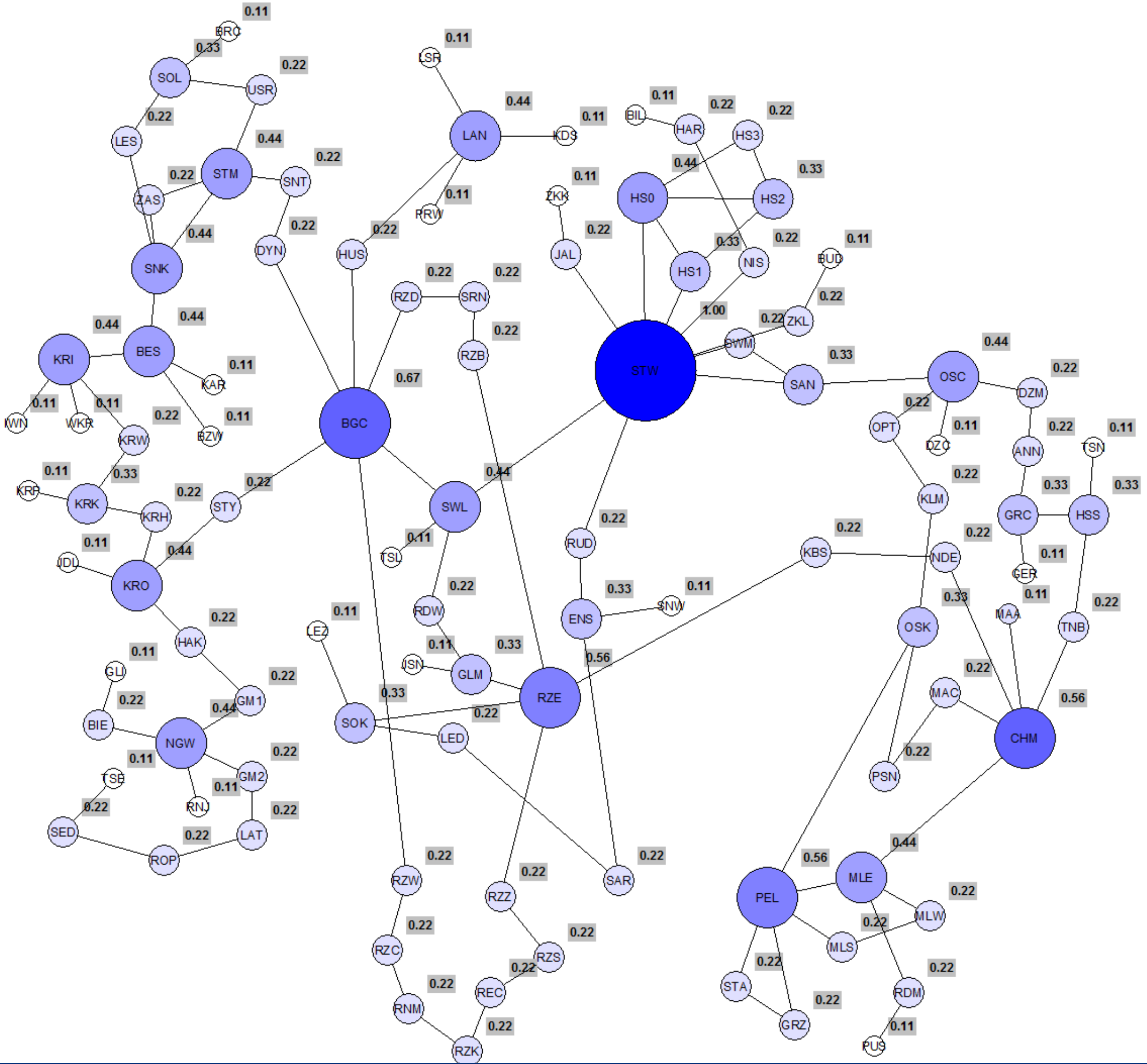
Previous research

Analysis of the degree of vertices in a graph (graph centrality analysis). The intensity of the blue color and the size of the node refer to the size of the node refer to the degree of the node. The numbers refer to the fraction of the node's degree relative to the STW node (Stalowa Wola power grid node).



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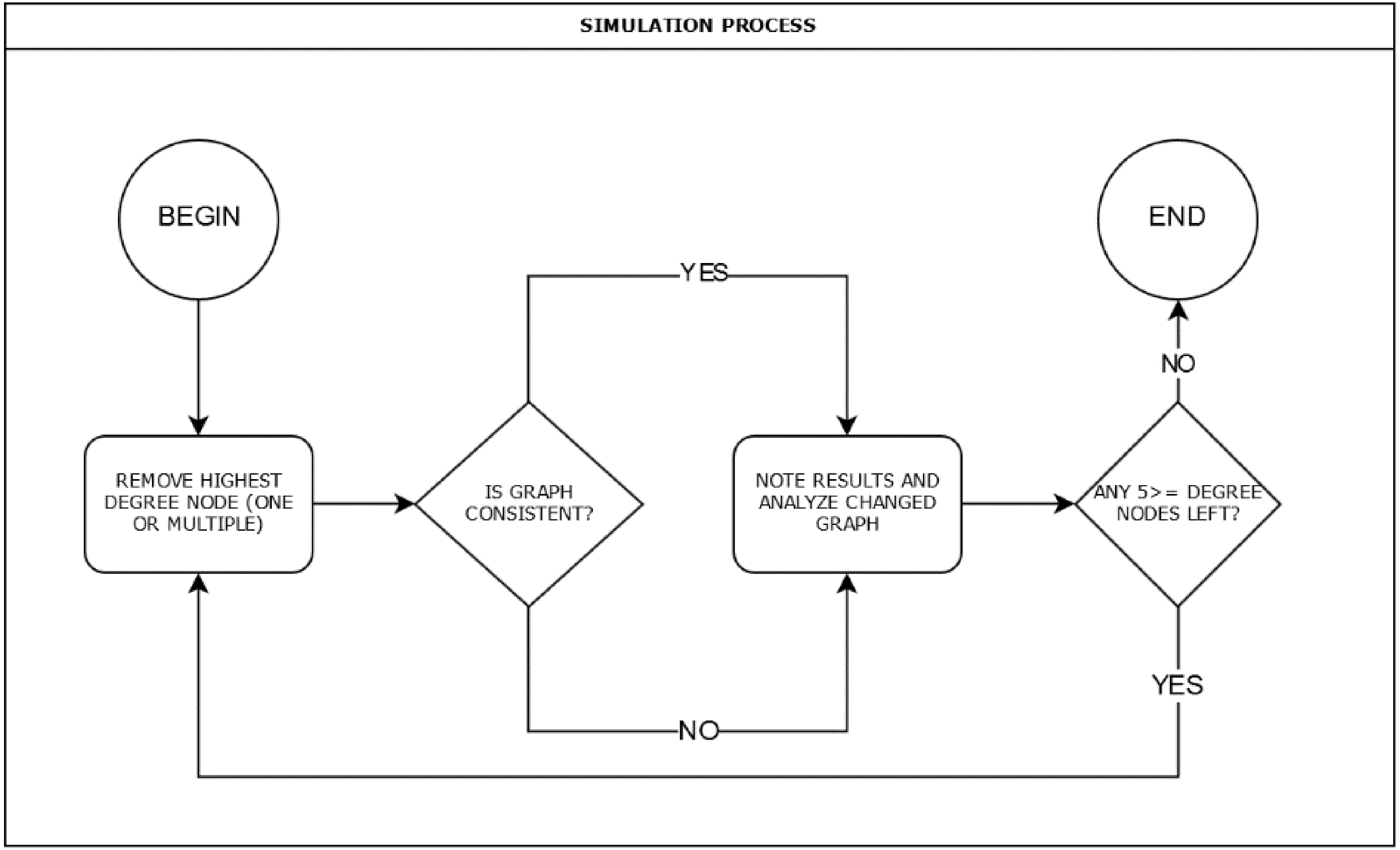
Previous research

Failure simulation algorithm



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Previous research

Disabled nodes	0	1	2	3	4	5
Number of nodes in the graph	102	101	100	99	98	97
Number of edges in the graph	116	107	101	96	91	86
The average node degree	2.275	2.119	2.020	1.939	1.857	1.773
Graph density	0.023	0.021	0.020	0.020	0.019	0.018
Local graph efficiency	0.081	0.070	0.071	0.065	0.058	0.052
Average graph efficiency	0.182	0.135	0.088	0.070	0.059	0.050
Average clustering coefficient	0.099	0.095	0.104	0.100	0.094	0.119
Average path lenght	7.661	9.140	6.619	5.894	5.612	5.643
Graph diameter	20.000	25.000	18.000	17.333	17.000	17.000

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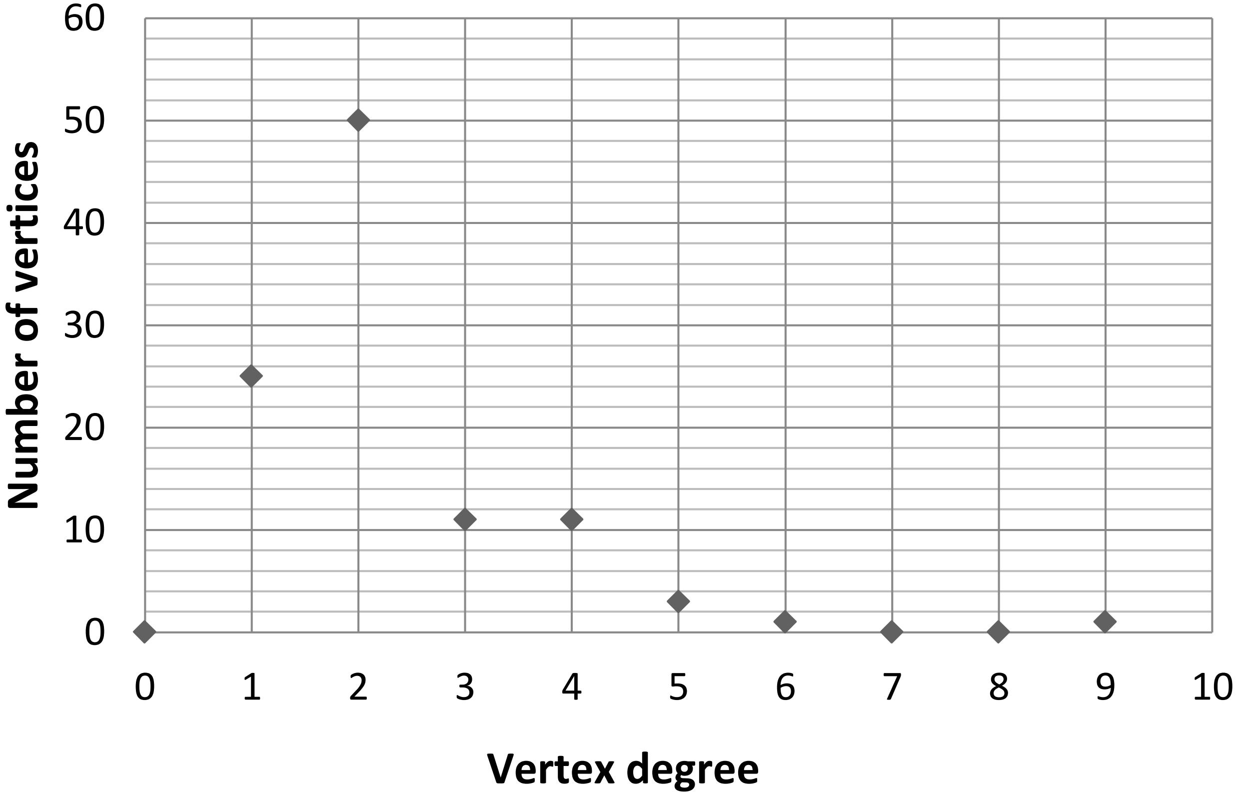
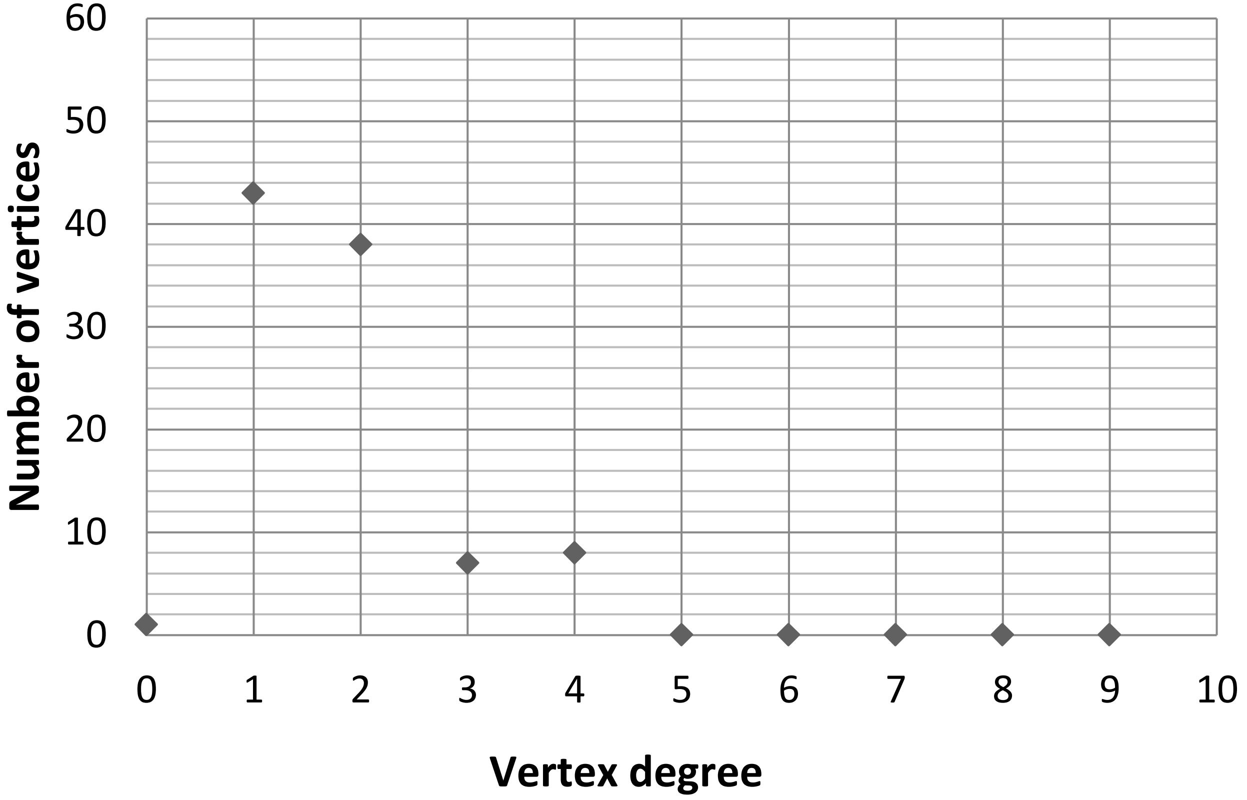
Previous research





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PLANS and NetworkX

1. Source data
2. Transfer of data to the graph.
3. Comparative analysis of the simulations performed in both software packages.
4. Software packages
5. Algorithms of calculation
6. Calculations
7. Results and conclusions.

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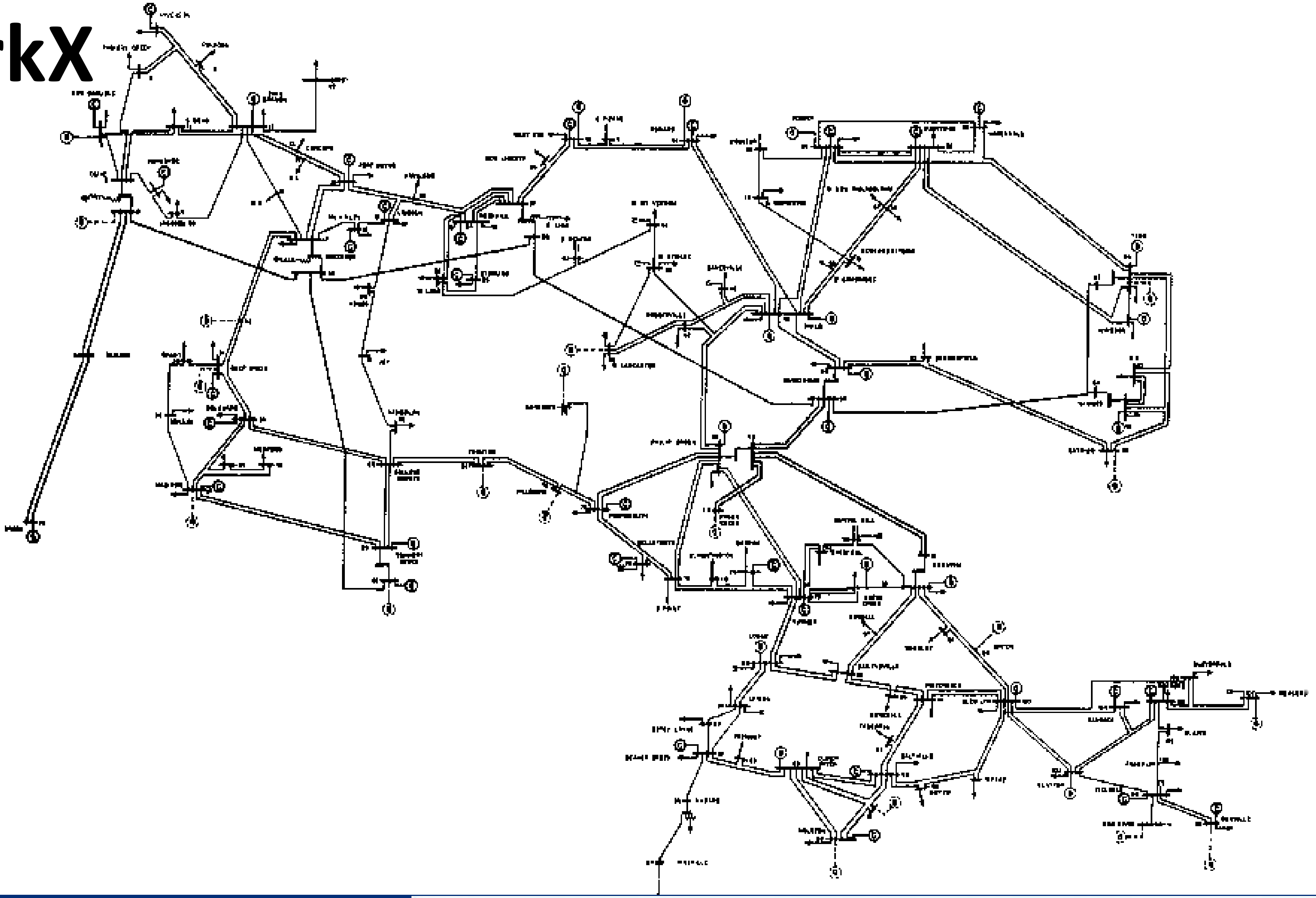
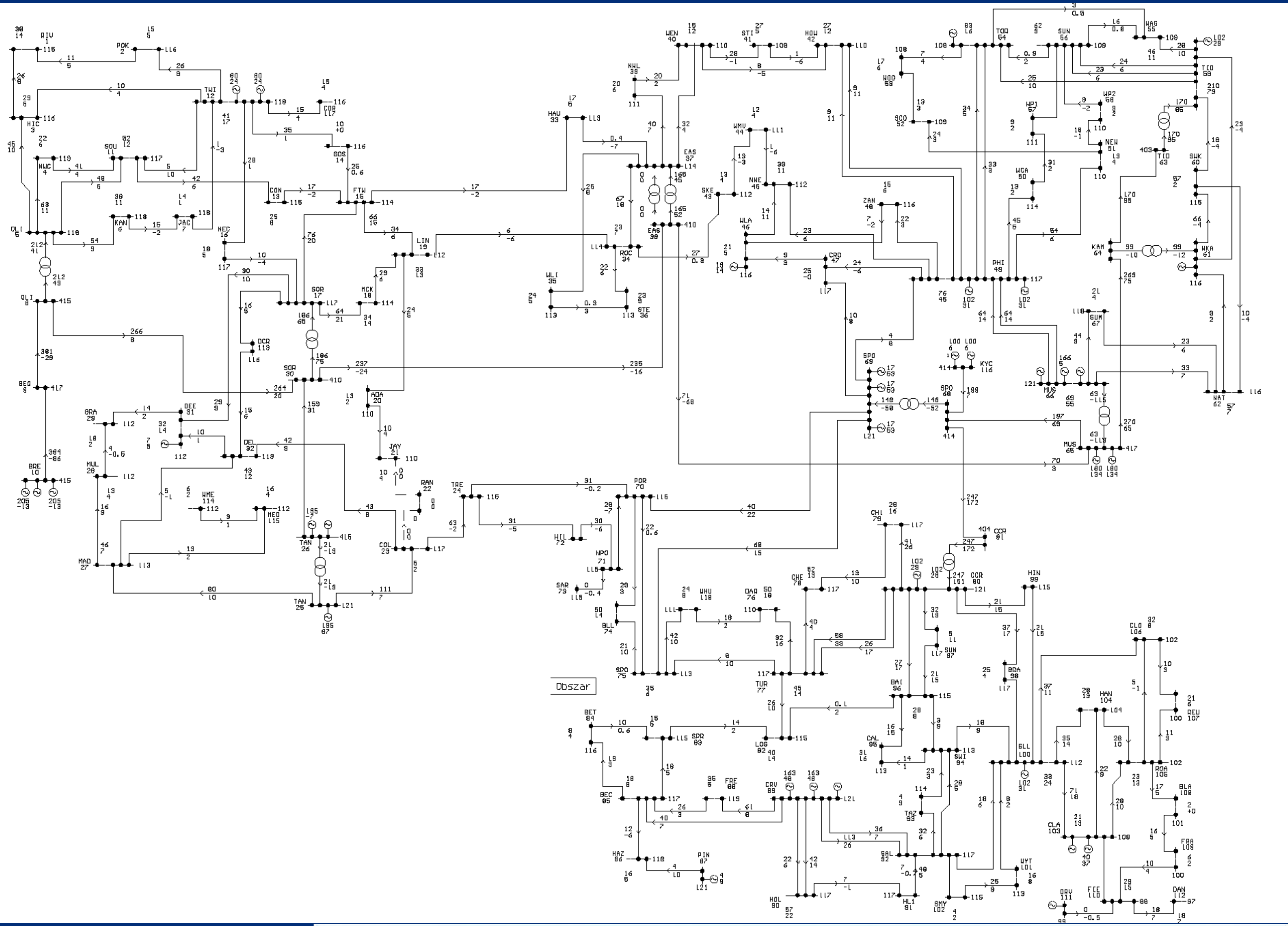
PLANS and NetworkX



Source data IEEE118 – 1962.

PLANS and NetworkX



Modernized scheme - the format of the KDM in PLANS

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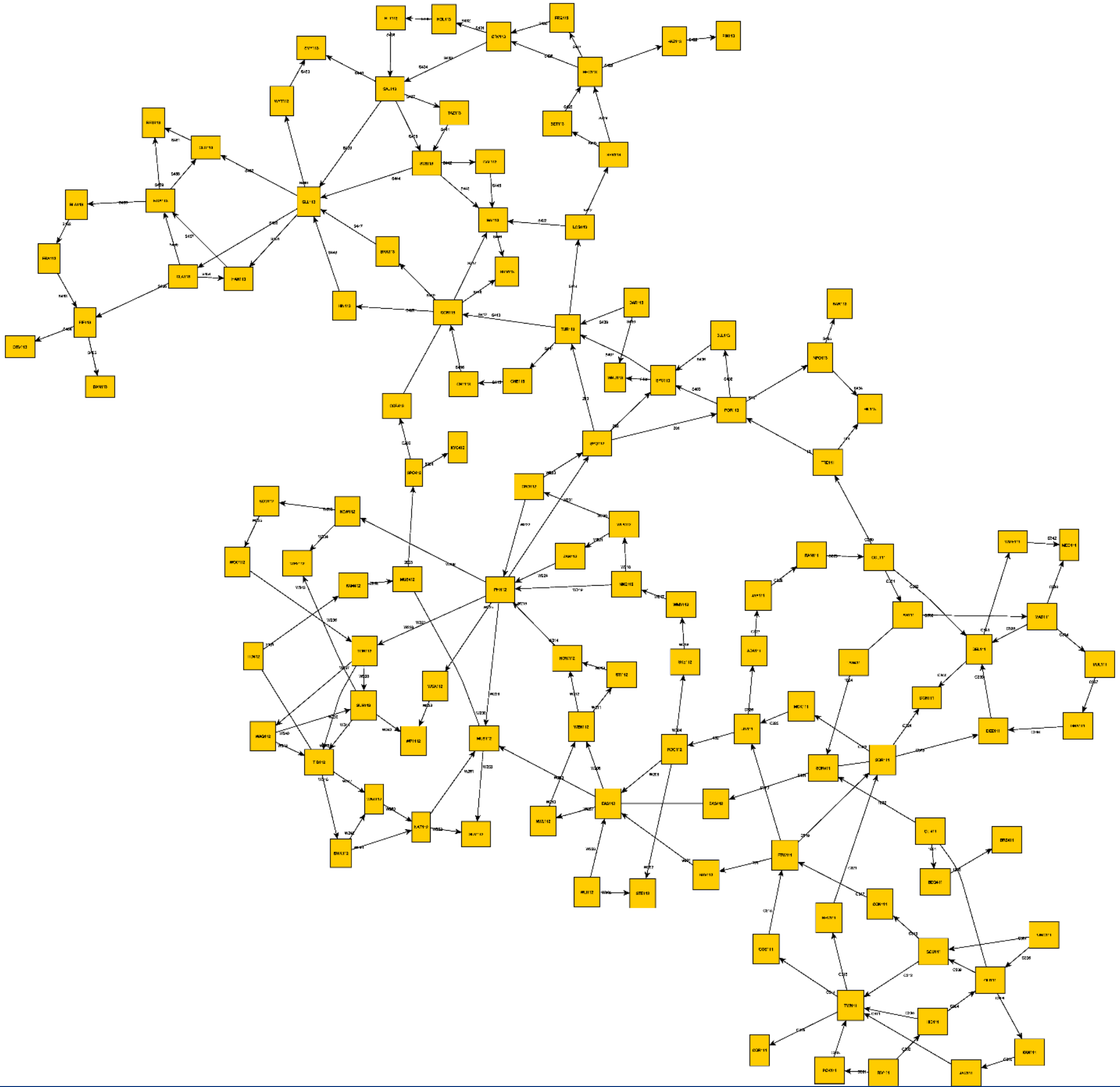
PLANS and NetworkX



Mathematical graph created on source data

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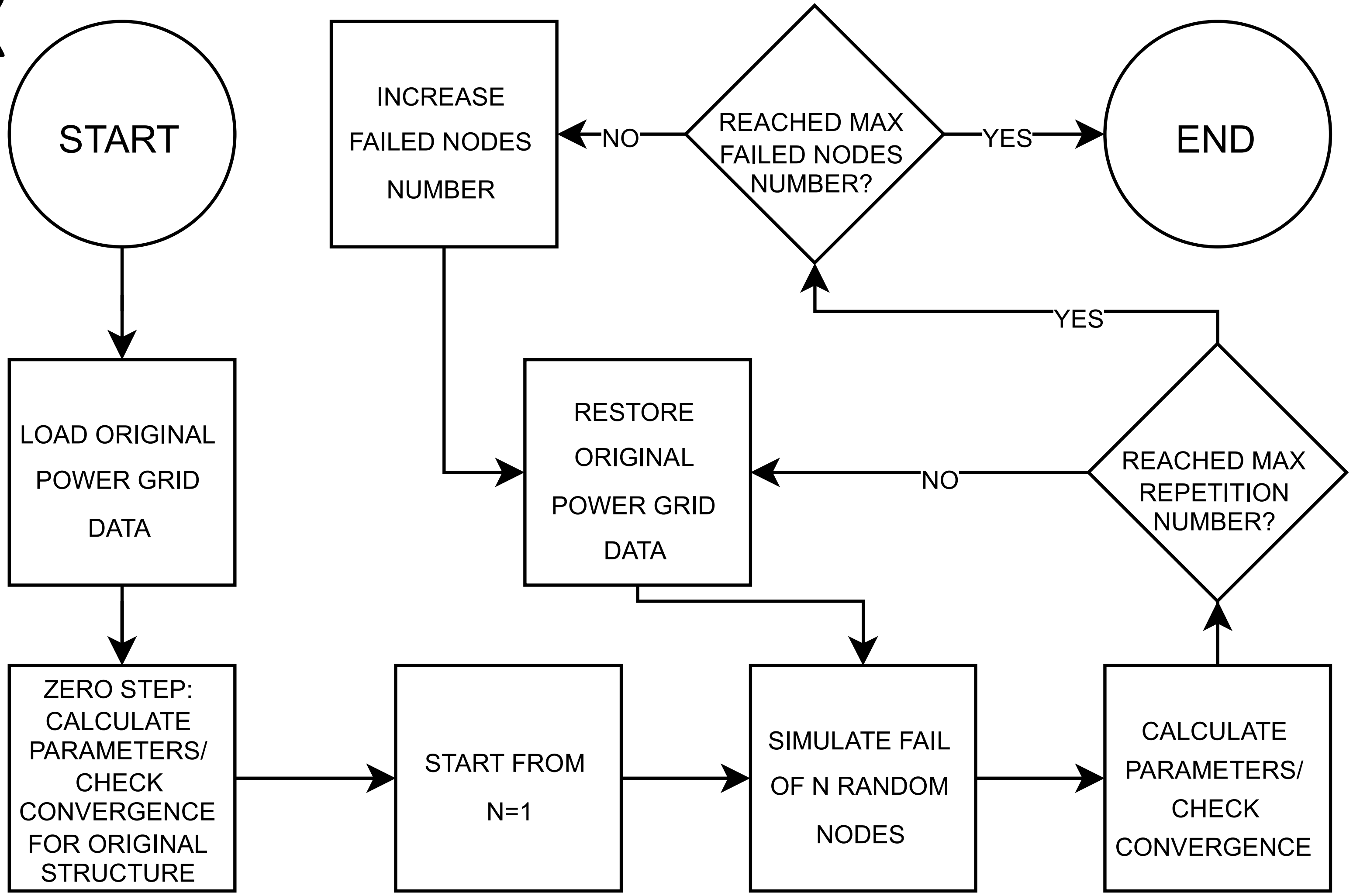
PLANS and NetworkX

Monte Carlo algorithm for simulating multiple random topology failures



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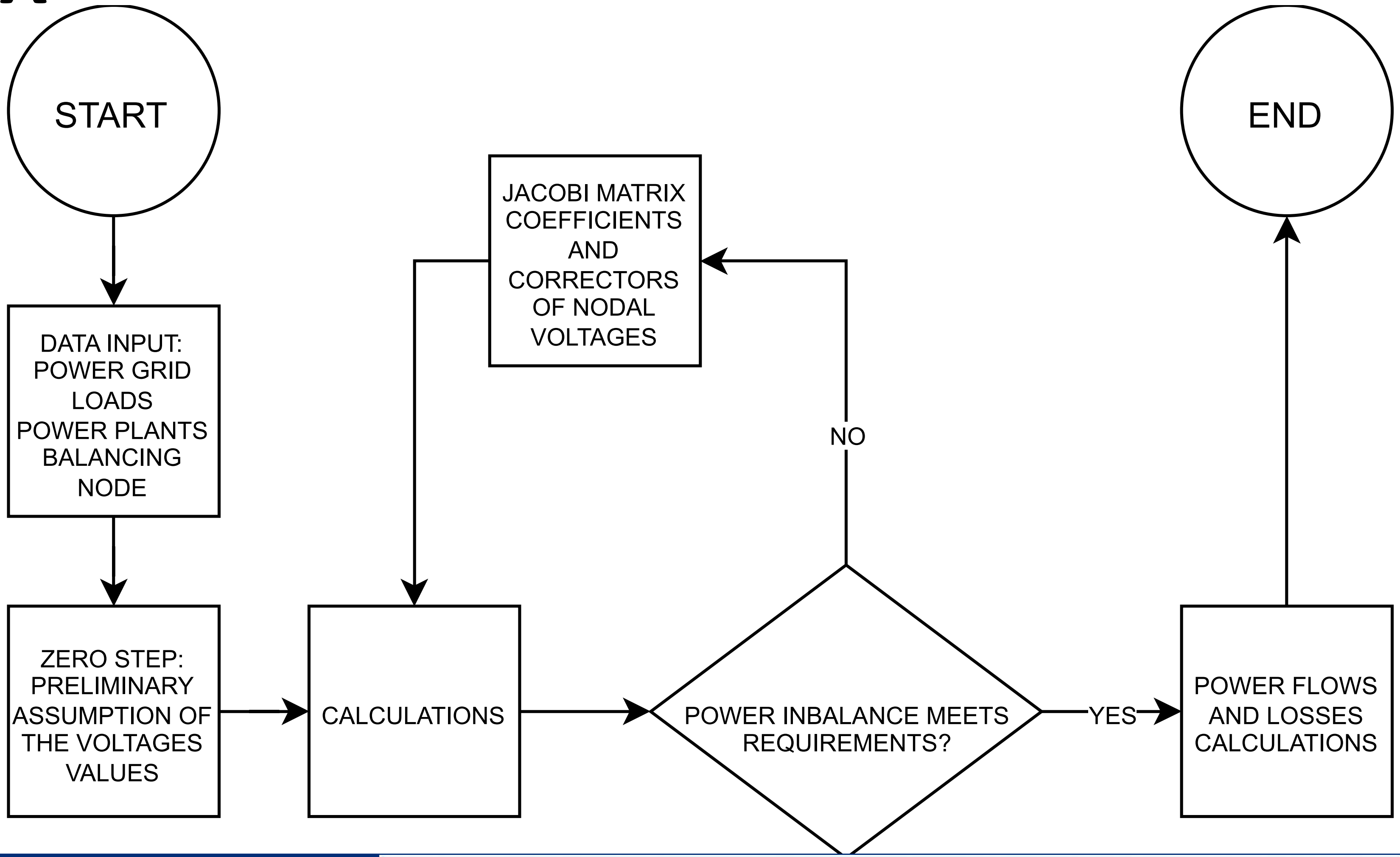
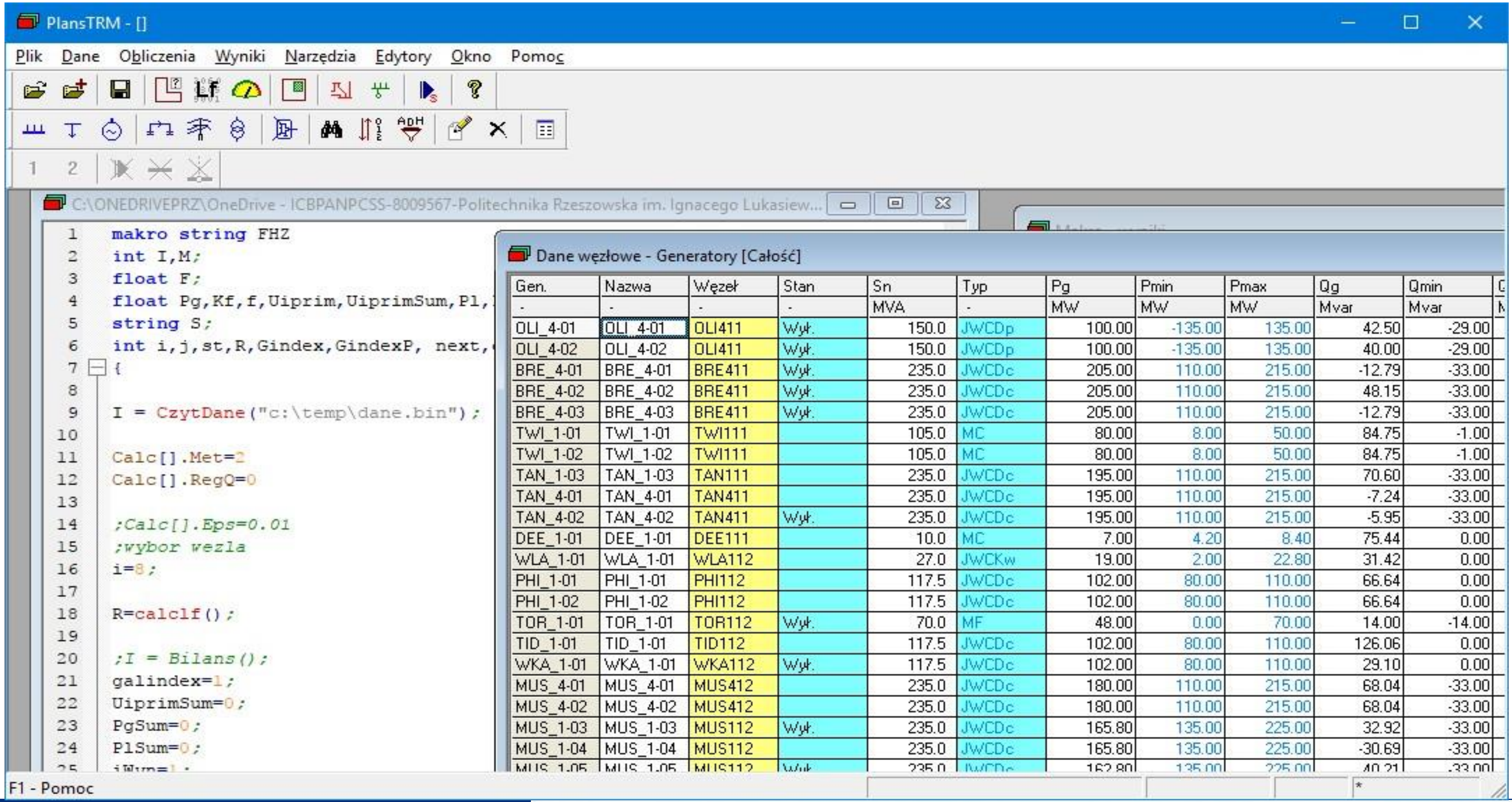
PLANS and NetworkX

Newton's algorithm for calculating power spreads in a power grid



PLANS and NetworkX

Simulations in PlansTRM - macro and generator table view



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NetworkX simulation results

Excluded nodes	Graph efficiency	Minimum observed efficiency	Average clustering coeficcient	Minimum observed local efficiency	% of PLANS imbalance cases
0	0.211691	0.211691	0.168032	0.175659	0
1	0.209994	0.192695	0.166500	0.153961	96.78 %
2	0.208472	0.178102	0.164964	0.133100	99.23 %
3	0.206406	0.164621	0.163118	0.124692	99.95 %
4	0.204678	0.153897	0.161576	0.112336	99.99 %
5	0.202462	0.131334	0.160204	0.102921	100 %

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Conclusions

1. The power grid is in good topological shape, but not very fault-tolerant.
2. Specialized software enables a more complete analysis of the network, taking into account unique parameters.
3. The Monte Carlo method compares simulated failures in different environments.
4. Future research may focus on making the network more resilient by adding redundancy.
5. It is necessary to include worst-case scenarios and larger data models in network analysis.
6. Focusing on worst-case scenarios in network analysis is the key.
7. Simulations using PLANS and the Monte Carlo method confirm the value of worst-case analysis.

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Current research

1. Extracting data from OpenStreetMap (OsmNX)
2. Transferring data to a mathematical graph (NetworkX)
3. Simulation of network damage for different variants (multiple repetitions for random elements)
4. Analysis of graph parameters for each variant (averaged results)

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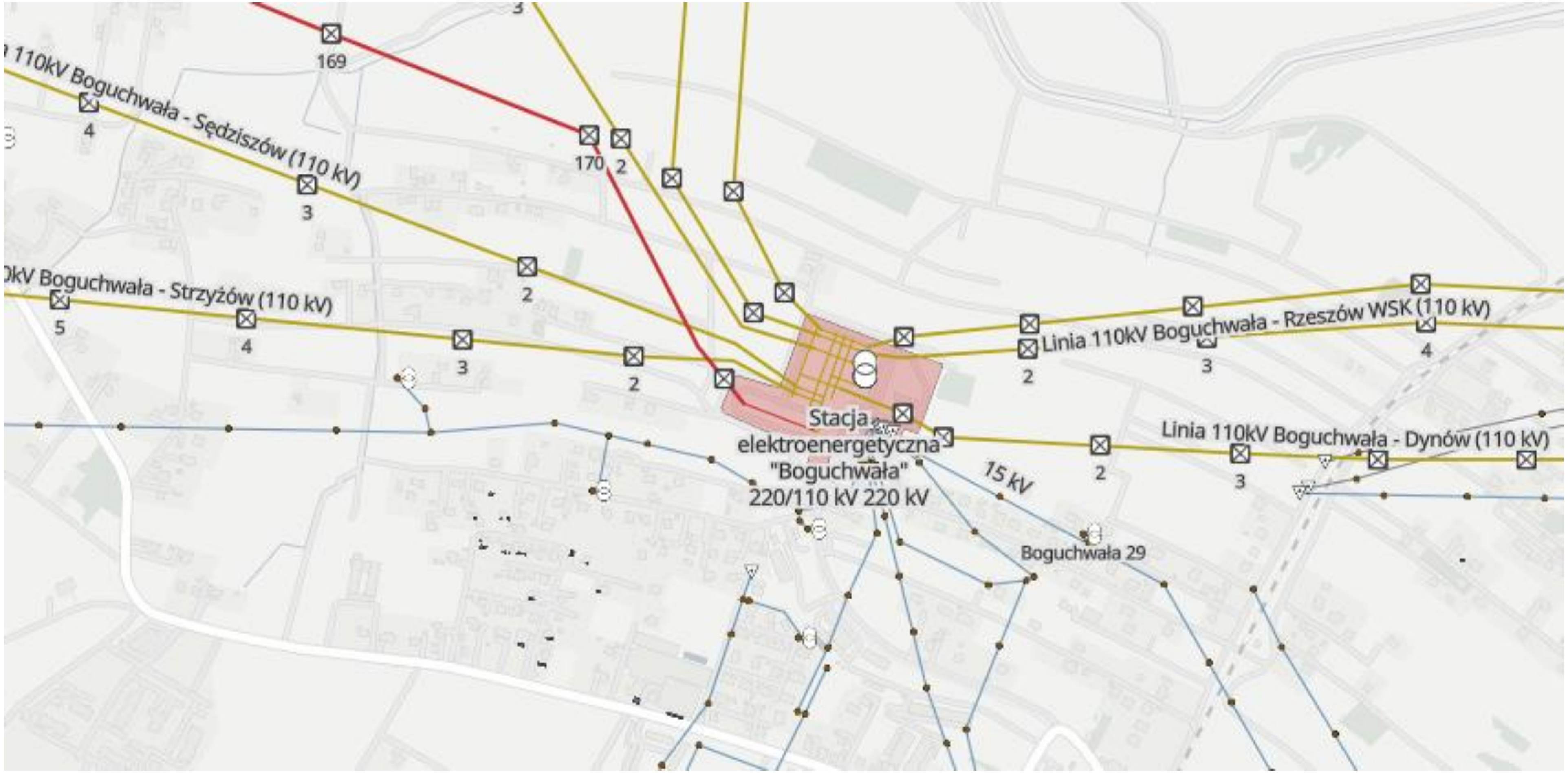
Current research



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Current research

Python language code that loads a graph from a file and performs calculations (part)

```
import networkx as nx
import numpy as np
import os
import math

for filename in os.listdir('.'):
    if filename.endswith('.graphml'):
        print('wczytywanie pliku '+filename)
        G = nx.read_graphml(filename)


        print('obliczenia dla '+filename)

        n = G.number_of_nodes()

        m = G.number_of_edges()
        print("liczba węzłów "+str(n)+", liczba krawędzi "+str(m))
        k = np.mean([d for n, d in G.degree()])
        r = nx.radius(list(G.subgraph(c) for c in nx.connected_components(G))[0])
        d = nx.diameter(list(G.subgraph(c) for c in nx.connected_components(G))[0])
        C = nx.transitivity(G)
        CC = nx.average_clustering(G)
```

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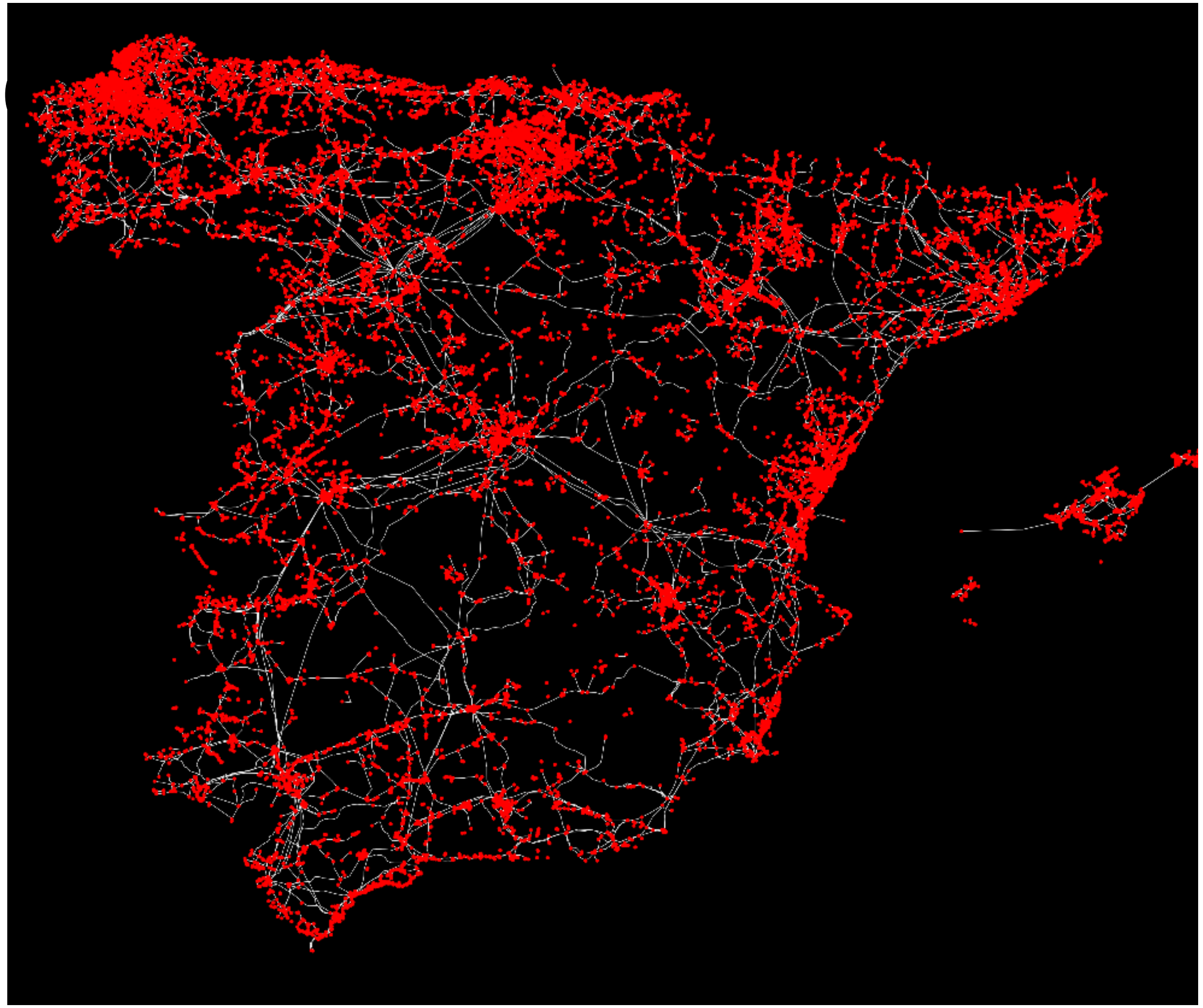
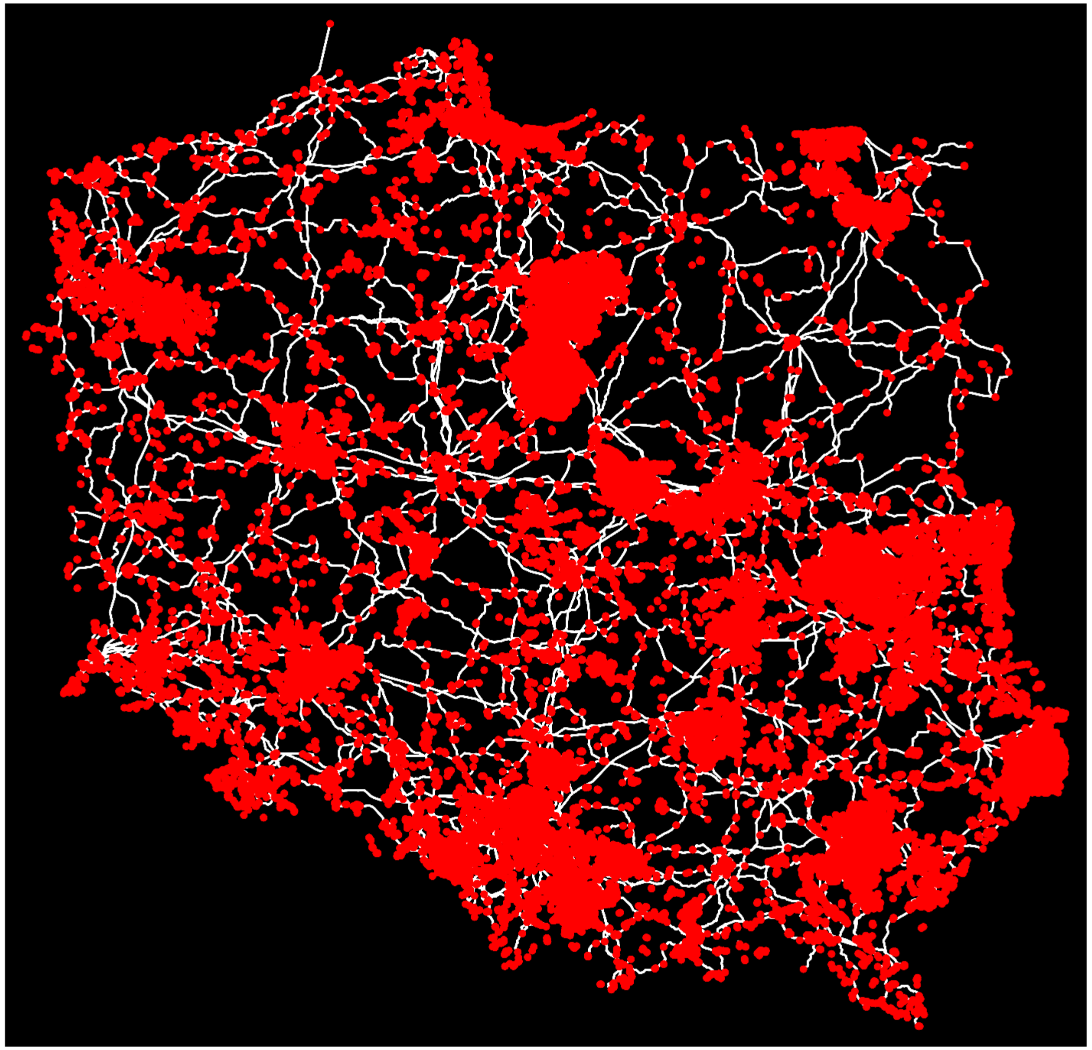


Spain



Poland

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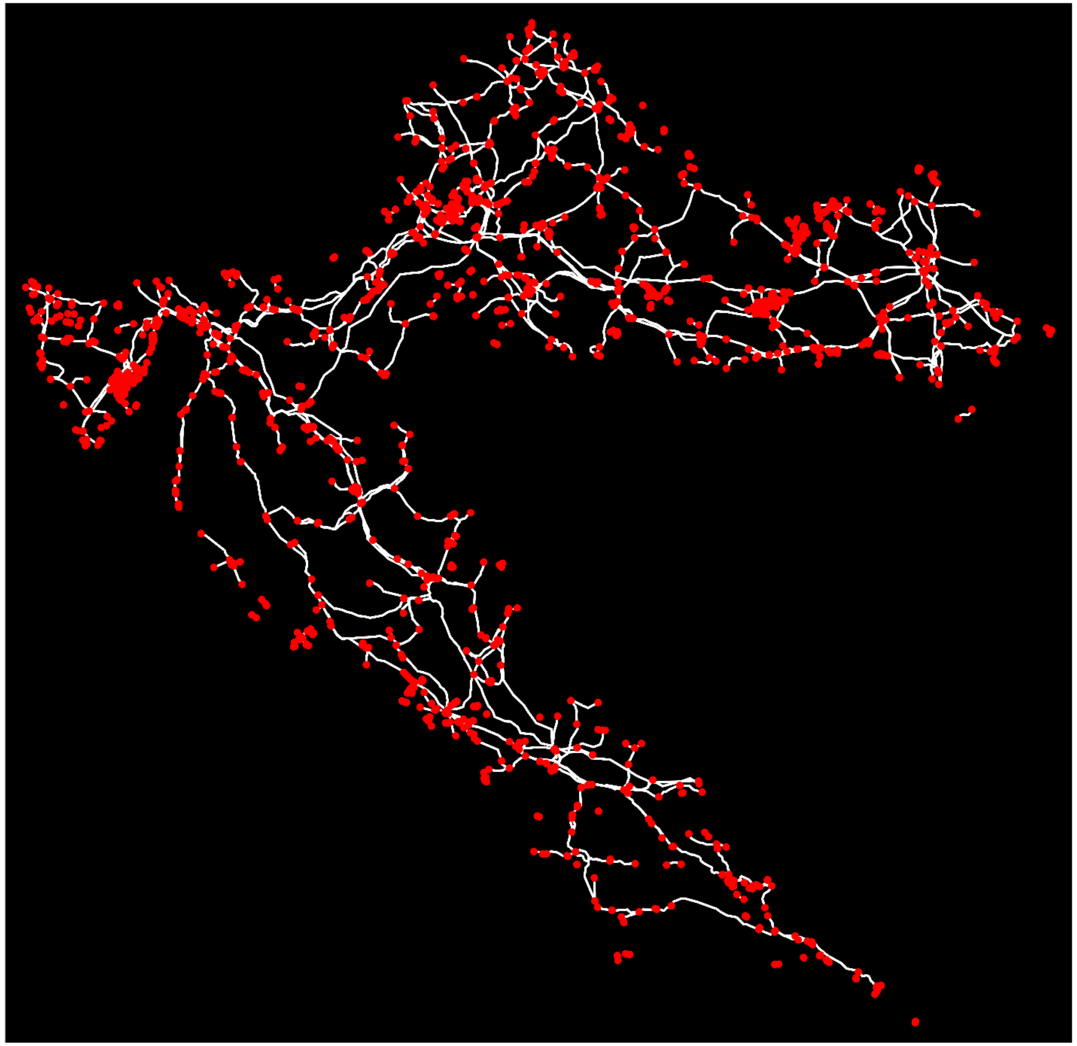
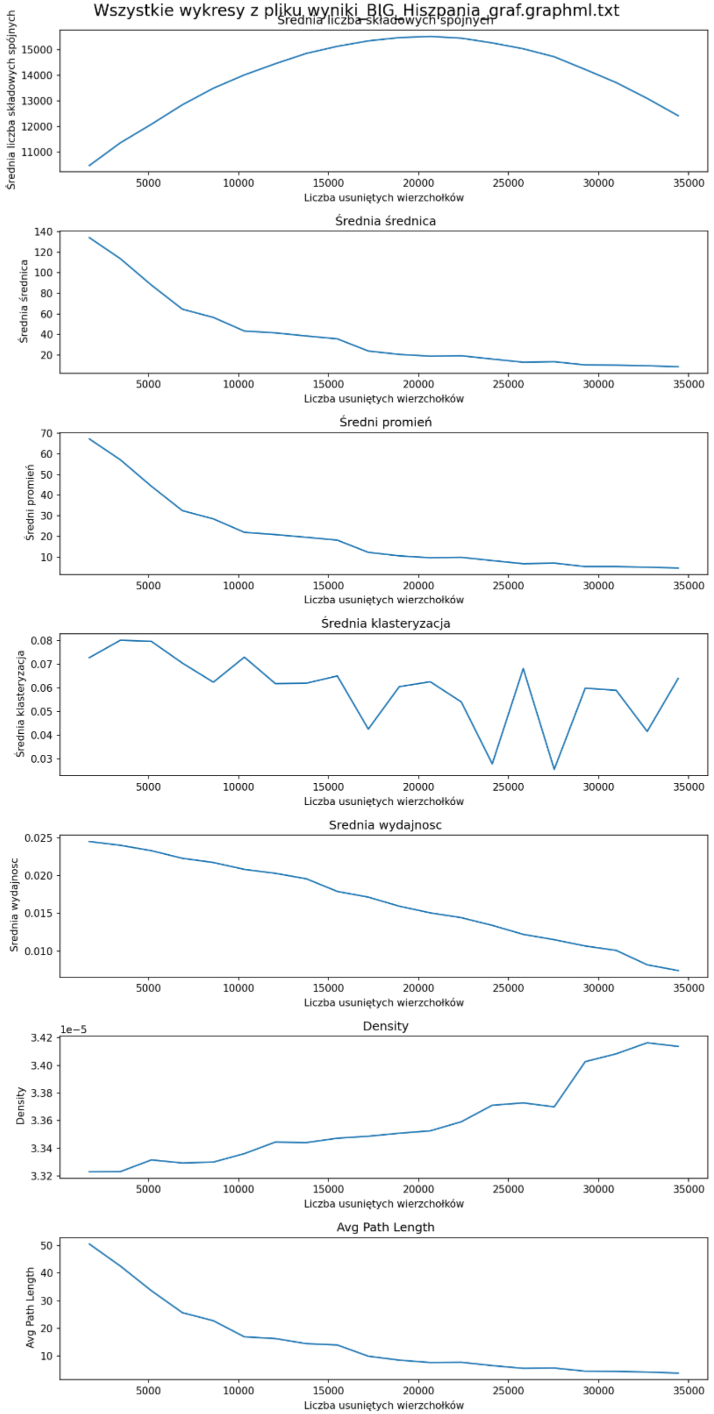
Current research

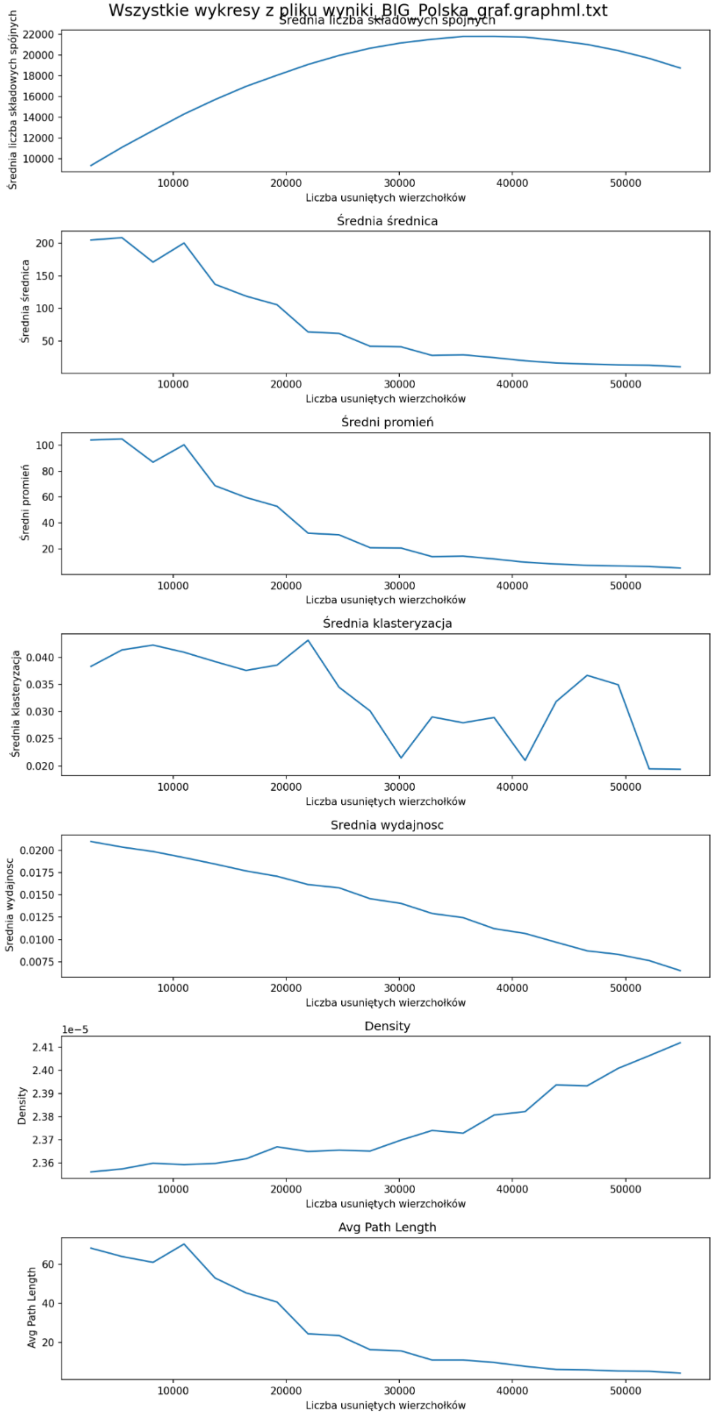

Finland


Croatia

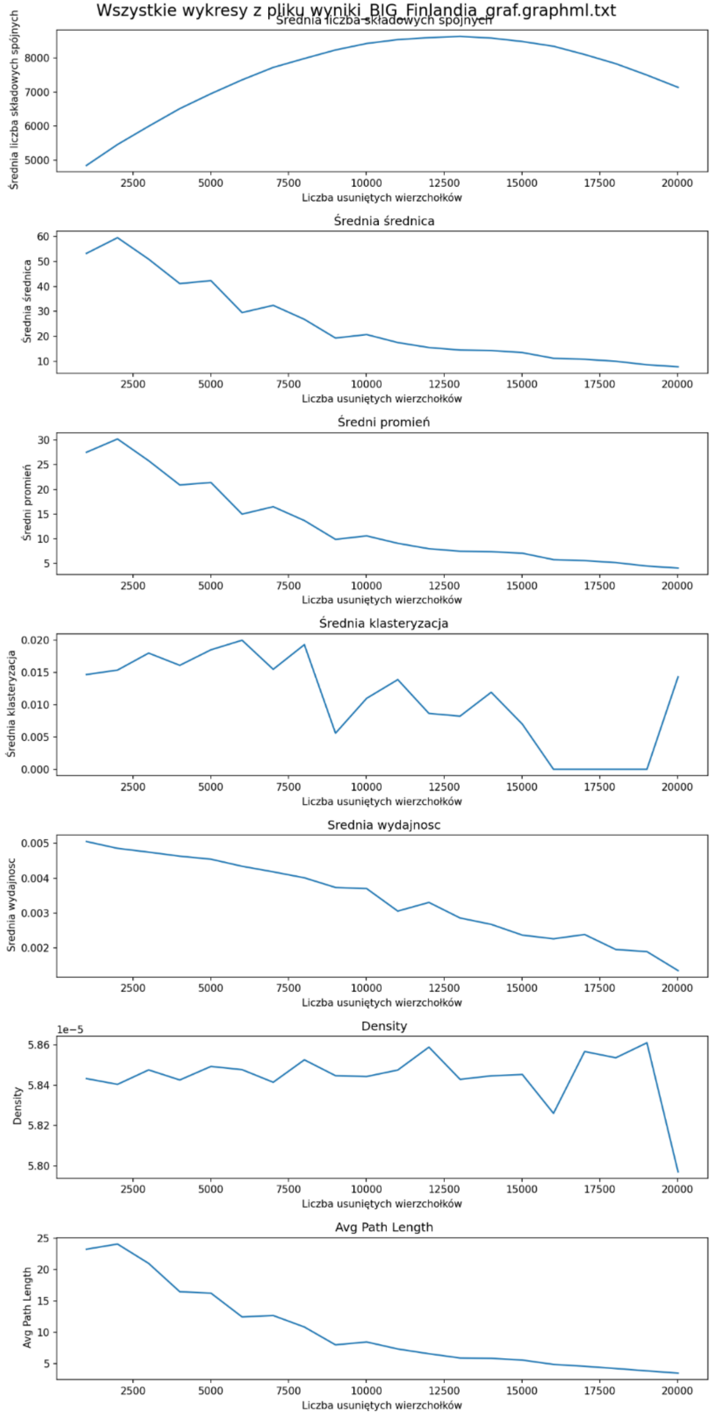
Wszystkie wykresy z pliku wyniki_BIG_Hiszpania_graf.graphml.txt



Wszystkie wykresy z pliku wyniki_BIG_Polska_graf.graphml.txt



Wszystkie wykresy z pliku wyniki_BIG_Finlandia_graf.graphml.txt



New research directions

- Simulation of failure of a larger number of nodes, > 15%.
- Simulation of failure in a specific geographic region.
- Simulation of failure under dynamic conditions.
- Simulation of the failure of the edges/top nodes.

Summary

- Fairly detailed data from OSM
- Lack of typical diagrams - safety issues
- Lengthy simulation calculations - graphs contain up to hundreds of thousands of nodes

Thank you for your attention

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