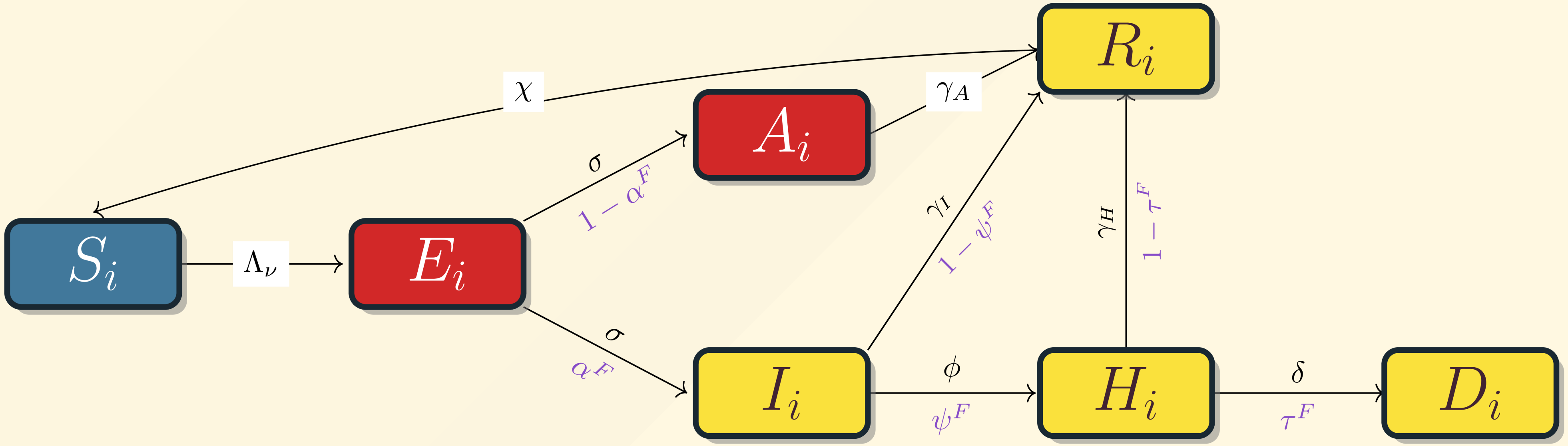
Analysis of COVID-19 Vaccination Strategies Based on Complex Networks

UFC

COVID CONTEXT

- Virus spread and high mortality rate
- High costs and time required for vaccine development:
  - Research
  - Storage
  - Distribution
- Therefore, efficient vaccination strategies are urgently needed!!!

Proposed Infection Model



DATA COLLECTION - NETWORK

- In 2008, the European Commission created the POLYMOD project to study contact patterns in Europe.
- Surveys conducted via random calls or interviews in 8 European countries:
    - Personal and environmental information (school, work, home, etc.).
    - Details about daily physical contacts (age, duration, frequency).

https://socialcontactdata.org/

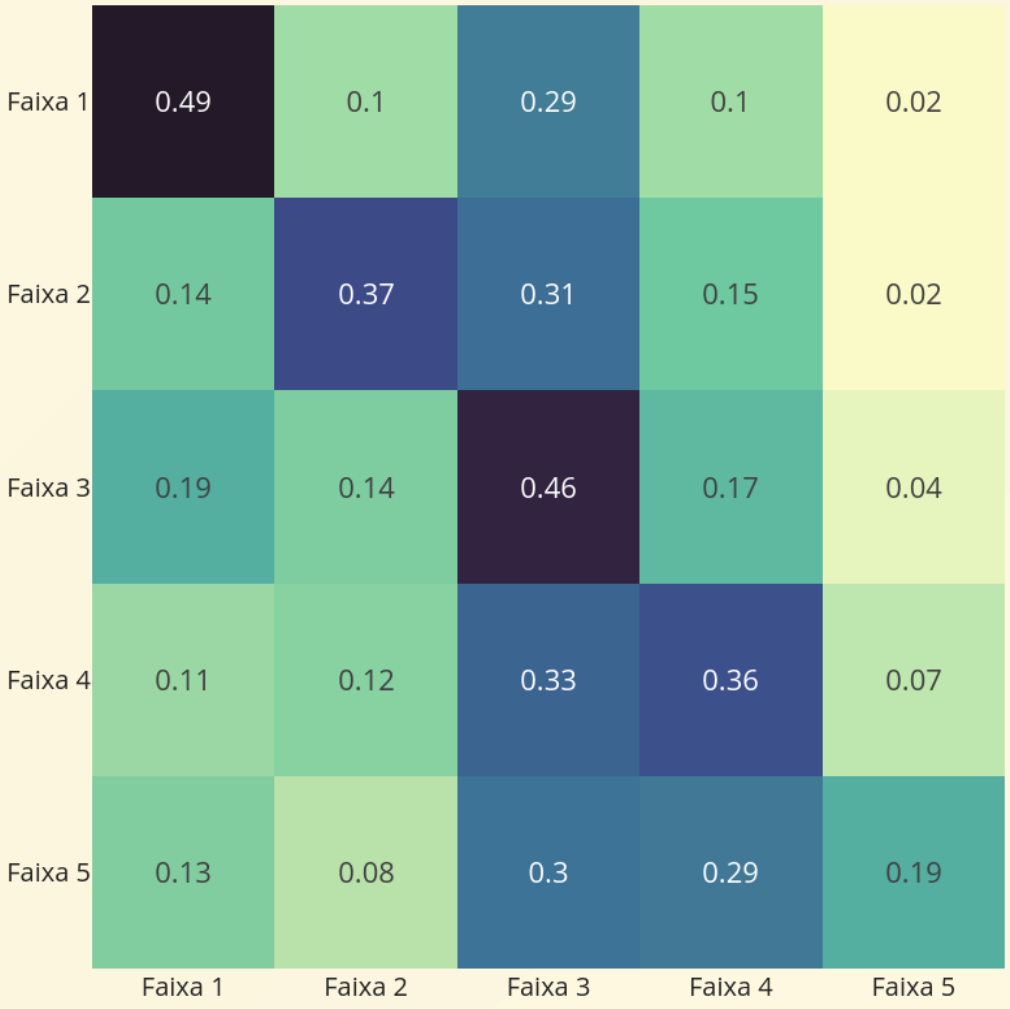
DATA COLLECTION - NETWORK

*The POLYMOD project (2005-2006, 8 European countries) provides valuable empirical data from contact diaries.
* Collected participant age, contact's age, interaction time.
* Sample representative but oversampled younger age groups.

- POLYMOD data yields ego-centric networks (star graphs), not a complete population contact graph, posing a challenge for direct network modeling.

- **Methodology (Manzo & van der Rijt):** A synthetic network is generated using:
    1. **Stratified Configuration Model:** Assigns node degrees based on POLYMOD's mean daily contacts, matching the empirical degree distribution.
    2. **Triadic Closure:** Enhances clustering by connecting neighbors with probability `p`.
- **Outcome:** The parameter `p` adjusts clustering, creating networks with realistic local structures.

DATA COLLECTION - NETWORK



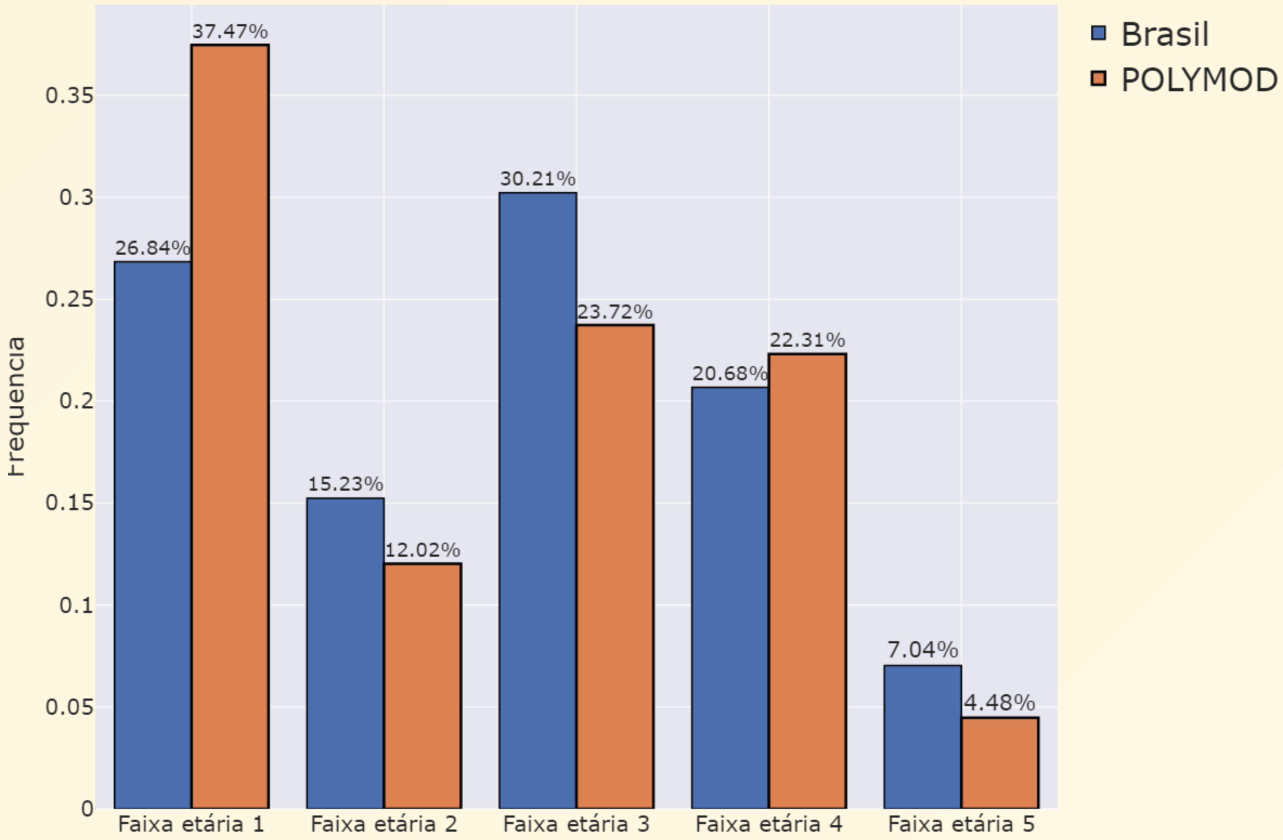
DATA COLLECTION - NETWORK

Faixa Etária	Faixa 1	Faixa 2	Faixa 3	Faixa 4	Faixa 5
Faixa 1	173.36	132.58	151.53	122.38	119.5
Faixa 2	132.58	123.83	93.86	89.14	78.31
Faixa 3	151.53	93.86	99.52	81.92	89.53
Faixa 4	122.38	89.14	81.92	110.09	87.53
Faixa 5	119.5	78.31	89.53	87.53	135.62

	Faixa 1	Faixa 2	Faixa 3	Faixa 4	Faixa 5
	118.05	117.75	123.27	110.97	109.13
	117.75	112.14	111.13	107.44	96.37
	123.27	111.13	112.82	101.88	102.43
	110.97	107.44	101.88	116.49	99.57
	109.13	96.37	102.43	99.57	114.35

Data Collection - COVID

- Data collected from various literature articles and OpenDataSus.
- Age group distribution used was based on Brazil's population.



Simulation

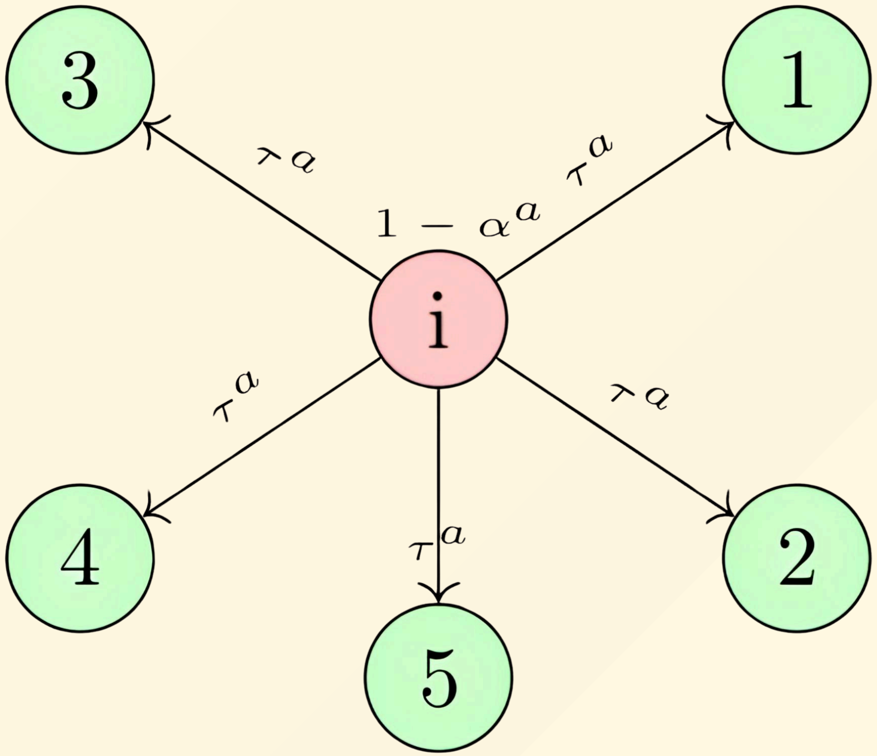
- The simulation lasts 465 days;
- On day 100, a fraction of the population in the Susceptible, Recovered, Asymptomatic, or Exposed stages is vaccinated;
- If vaccines remain, other sites will be vaccinated as they enter those compartments.
- The simulation was conducted on a network of size 10,000 with 400 different networks.

Vaccination

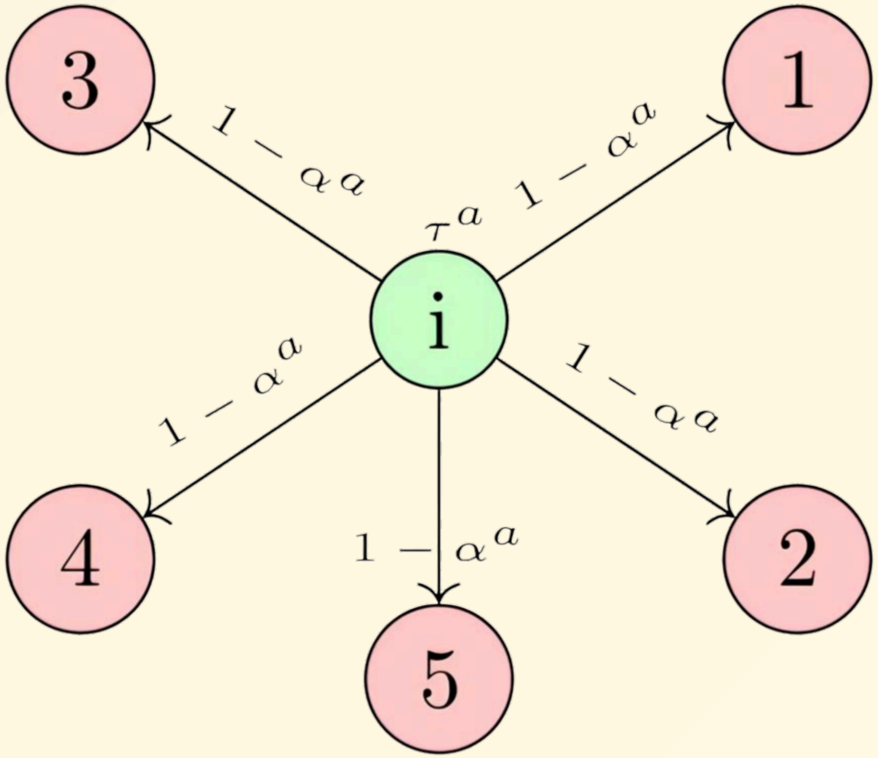
- More than 30 strategies based on centralities were used for networks without edge weights, and more than 60 for networks with edge weights;
- Three metrics were used: Fraction of Deaths, Total Hospitalization Time, and Fraction of Infected;
- For centralities that use node weights, two approaches were applied: Altruistic and Individualistic.

Vaccination

Altruistic



Individualistic



Altruistic Prioritizes nodes likely to cause severe outcomes in neighbors.

- $f_{\rightarrow}(\Theta(\nu)) = 1 - \alpha_{\nu}$ (P(Node ν becomes Asymptomatic))
- $f_{\leftarrow}(\Theta(\mu)) = \tau_{\mu}$ (P(Neighbor μ Dies if Symptomatic))

Individualistic Prioritizes nodes whose own risk is high, considering neighbors' potential to transmit.

- $f_{\rightarrow}(\Theta(\nu)) = \tau_{\nu}$ (P(Node ν Dies if Symptomatic))
- $f_{\leftarrow}(\Theta(\mu)) = 1 - \alpha_{\mu}$ (P(Neighbor μ becomes Asymptomatic))

$$UT(\nu) = \sum_{\mu \in \eta(\nu)} \left(\frac{w_{\nu,\mu} f_{\rightarrow}(\Theta(\nu))}{k_{\nu}^{w}} + \frac{w_{\nu,\mu} f_{\leftarrow}(\Theta(\mu))}{k_{\mu}^{w}} + \frac{w_{\nu,\mu} f_{\rightarrow}(\Theta(\nu))}{k_{\nu}^{w}} \times \frac{w_{\nu,\mu} f_{\leftarrow}(\Theta(\mu))}{k_{\mu}^{w}} \right)$$

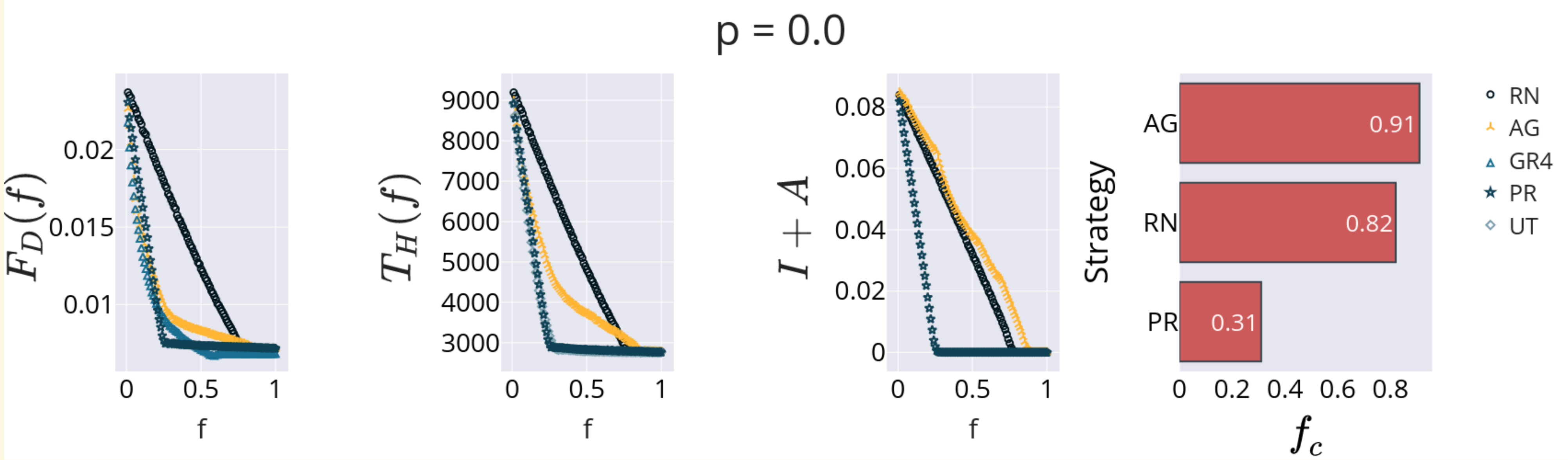
$$GR(\nu) = \sum_{\mu \neq \nu} \frac{f_{\rightarrow}(\Theta(\nu)) f_{\leftarrow}(\Theta(\mu))}{(d_{\nu,\mu}^{w})^{1/s}}$$

$$DA(\nu) = (1 - \alpha_{\nu}) \times \left(1 - \prod_{\mu \in \eta(\nu)} (1 - \alpha_{\mu} \psi_{\mu} \tau_{\mu}) \right)$$

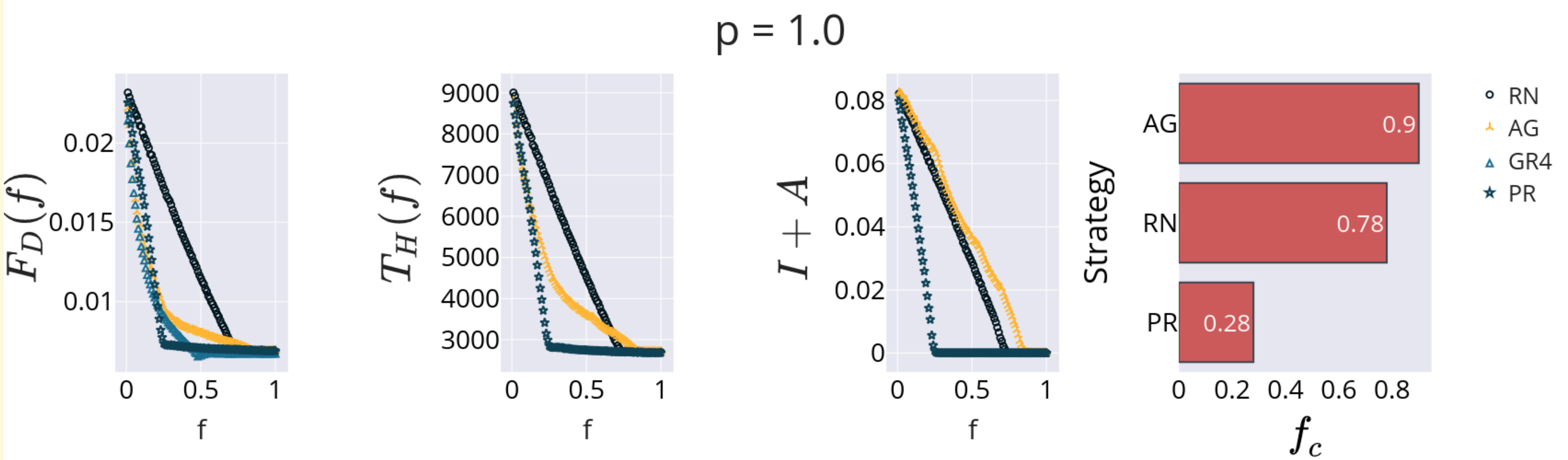
$$DD(\nu) = |\eta(\nu)| \alpha_{\nu} \psi_{\nu} \tau_{\nu}$$

$$HA(\nu) = (1 - \alpha_{\nu}) \times \left(1 - \prod_{\mu \in \eta(\nu)} (1 - \psi_{\mu}) \right)$$

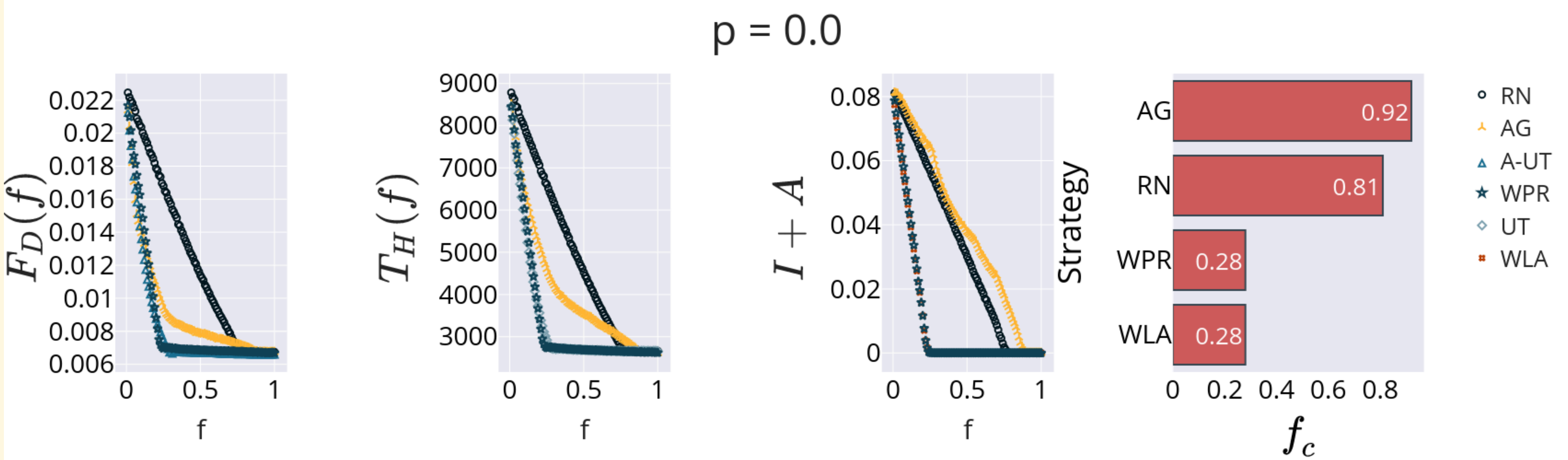
- **Goal:** Evaluate effectiveness of different node prioritization strategies for vaccination.
- **Metrics:**
  1. **Total Hospitalization Time (T_H)**: Area under $T_H(f)$.
  2. **Fraction of Deaths (F_D)**: Area under $F_D(f)$.
  3. **Fraction to Extinguish (f_c)**: Min fraction f for disease eradication.
  - Also used mean normalized rank across metrics.
- **Strategies:** Compared centrality-based (37 simple, 63 weighted/attribute-aware), Age-based (AG), and Random (RN).



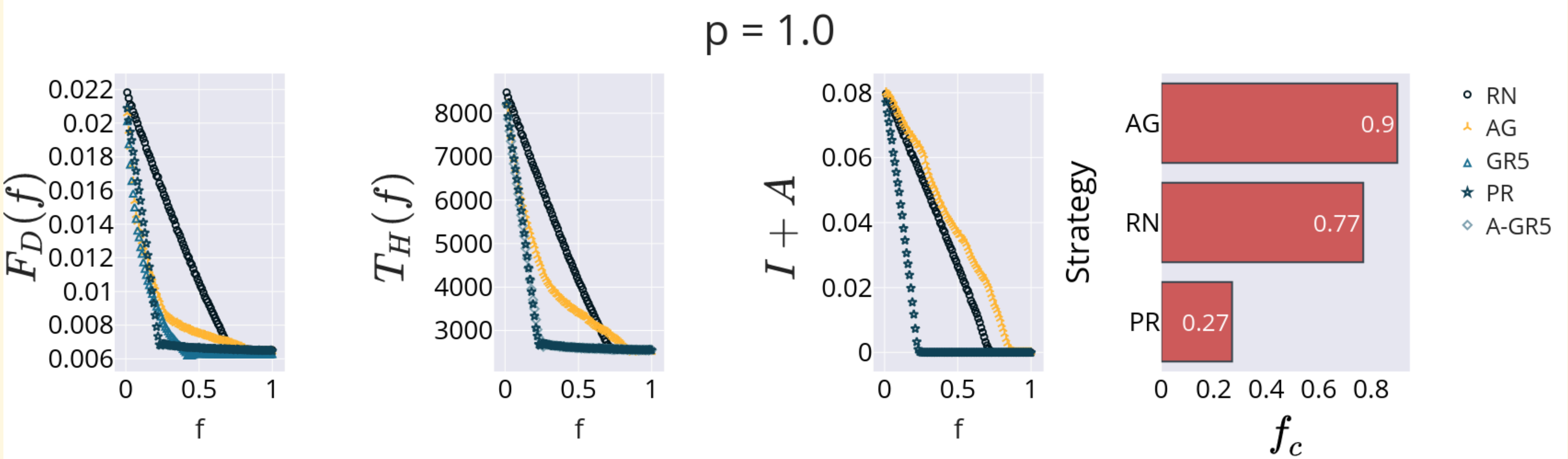
- **Age (AG):** Poor for extinction ($f_c \approx 90\%$, worse than RN), but reduces deaths/hospitalization at low f (<15%).
- **PageRank (PR):** Excellent for extinction ($f_c \approx 30\%$). Best on average.
- **Best vary by metric:** Gravity (GR4), Utility (UT), PageRank (PR).



- Findings consistent for p=1 (higher clustering).
- AG still poor for f_c.
- PR still strong, best on average.
- Specific best strategies remain similar.

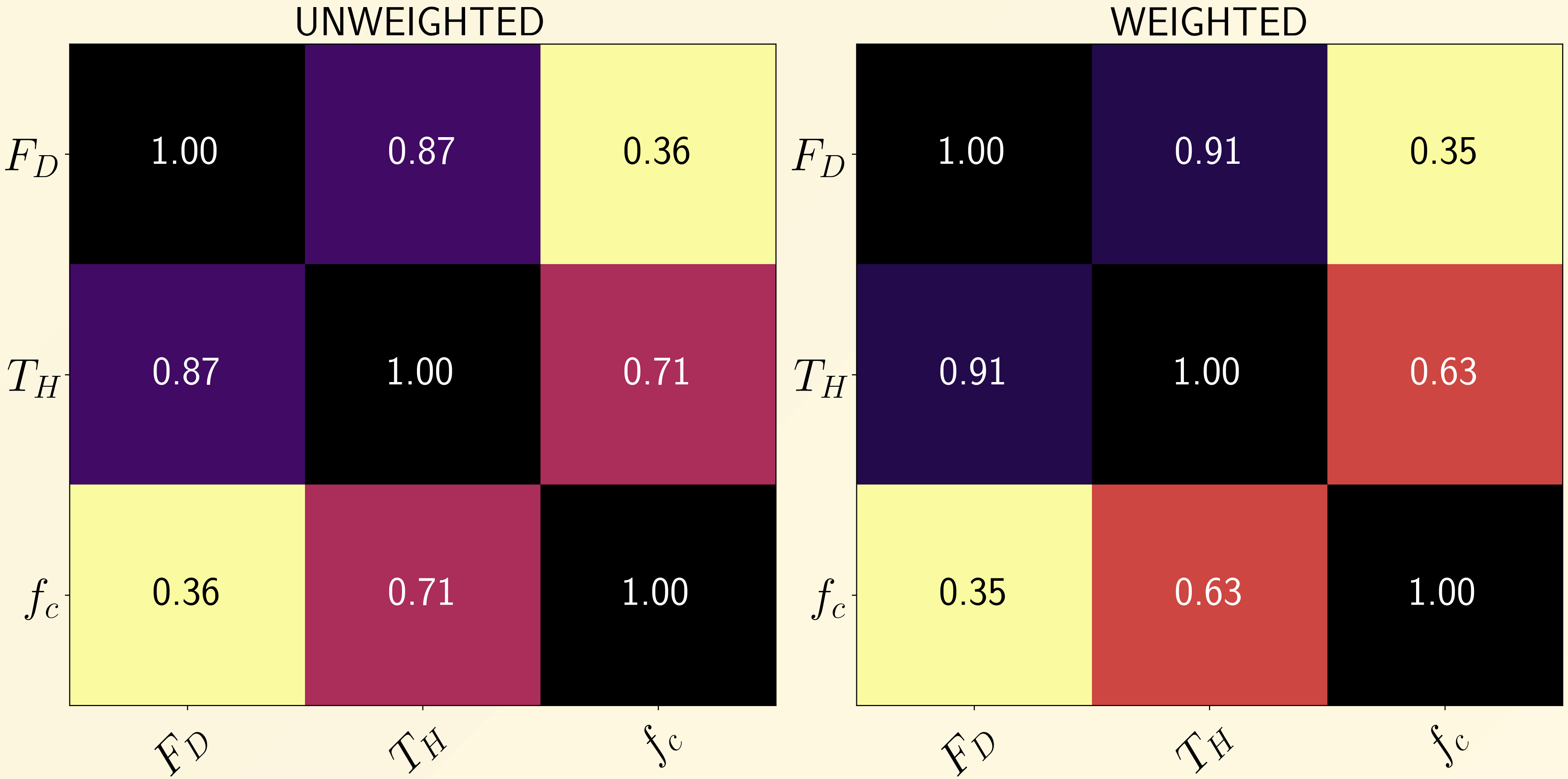


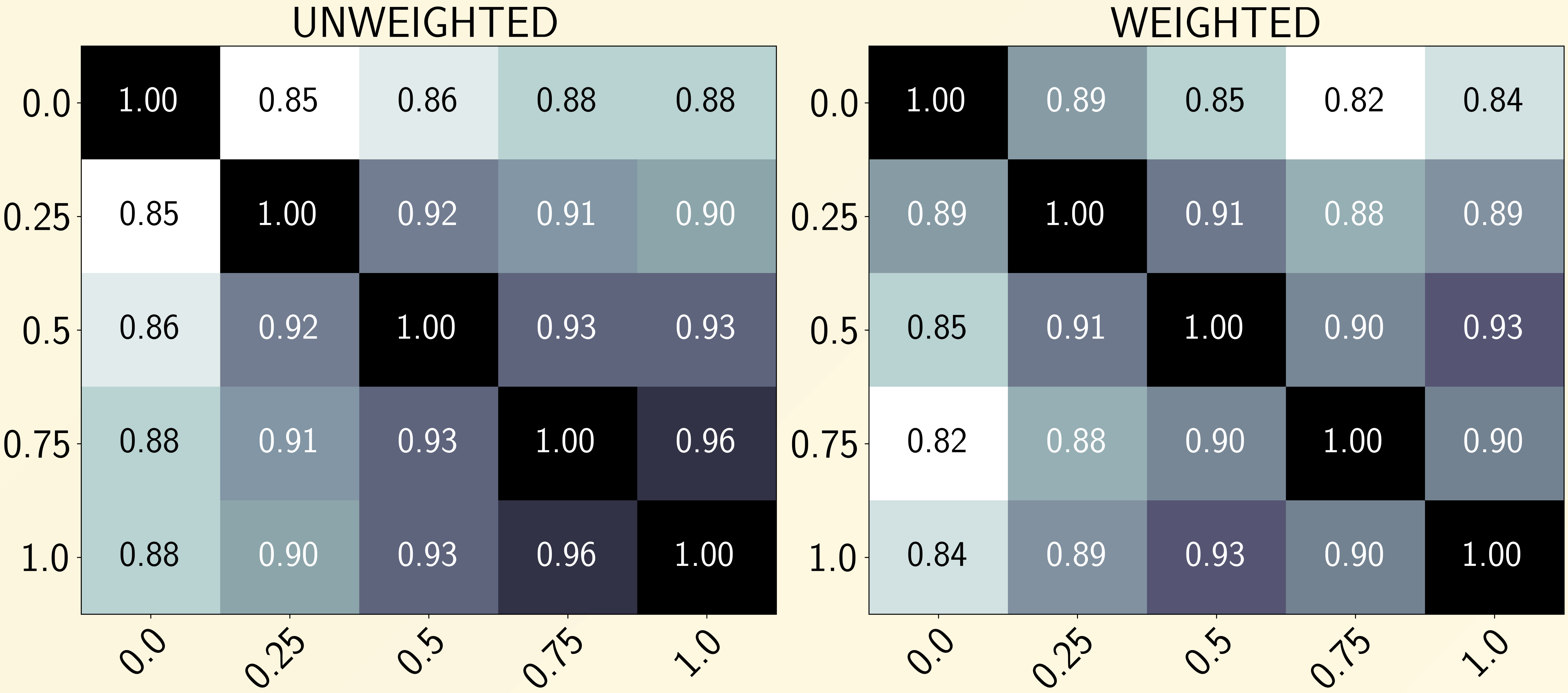
- Some shifts in best performers (e.g., Gravity variants, Weighted Laplacian, Weighted PageRank).
- **Weighted PageRank (WPR)** is best on average for p=0.
- AG strategy shows similar patterns (poor f_c, decent low-f F_D/T_H).



- **Unweighted PageRank (PR)** emerges as best on average for p=1, even on the weighted network.
- Overall, PageRank variants consistently perform well.

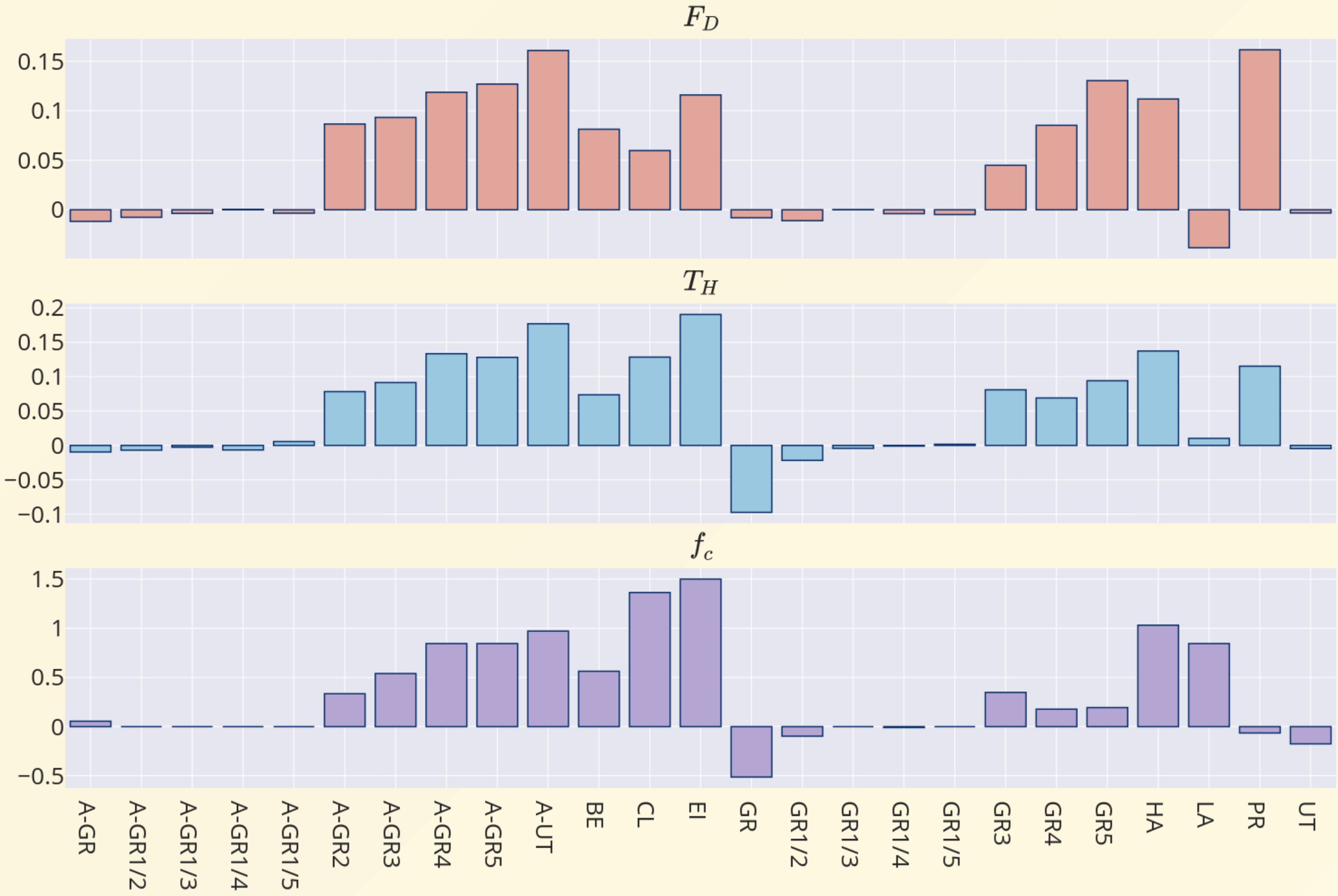
Metric Correlations & Clustering Robustness

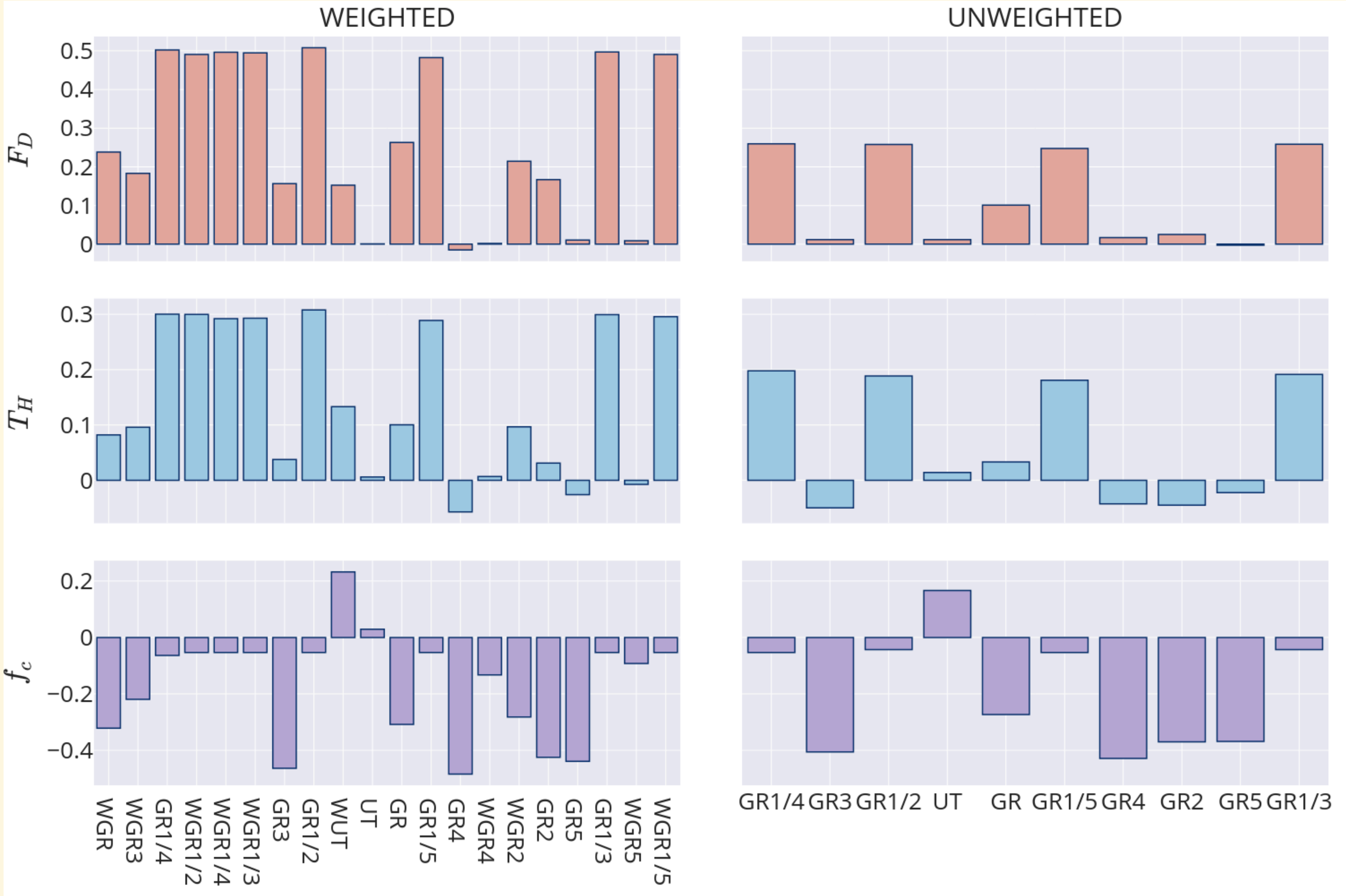



UNWEIGHTED
0.0
0.25
0.5
0.75
1.0
1.00 0.85 0.86 0.88 0.88
0.85 1.00 0.92 0.91 0.90
0.86 0.92 1.00 0.93 0.93
0.88 0.91 0.93 1.00 0.96
0.88 0.90 0.93 0.96 1.00
WEIGHTED
1.00 0.89 0.85 0.82 0.84
0.89 1.00 0.91 0.88 0.89
0.85 0.91 1.00 0.90 0.93
0.82 0.88 0.90 1.00 0.90
0.84 0.89 0.93 0.90 1.00

- **Metric Correlation:**
  - T_H and F_D rankings are strongly correlated.
  - f_c shows weak correlation with F_D, explaining AG's behavior.
- **Clustering Robustness:**
  - Strategy rankings remain consistent across different `p` values.
  - **Conclusion:** Strategy effectiveness is largely unaffected by clustering, ensuring real-world applicability.

- **Using Edge Weights in Centrality:**
  - Relative Difference: $Z^w = (M^w - M)/M$
  - **Finding:** Generally little benefit, often *worse* performance using weighted centrality measures. Closeness showed ~150% loss.
  - **Conclusion:** The computational cost of weighted centrality may not be justified.
- **Altruistic vs. Egoistic Measures:**
  - Relative Difference: $Z^A = (M^E - M^A)/M^A$
  - **Finding:** Egoistic strategies generally perform worse on weighted networks. Little difference on unweighted networks.


F_D
T_H
f_c
0.15
0.1
0.05
0
0.2
−0.05
−0.1
1.5
1
0.5
−0.5
A-GR
A-GR1/2
A-GR1/3
A-GR1/4
A-GR1/5
A-GR2
A-GR3
A-GR4
A-GR5
A-UT
BE
CL
EI
GR
GR1/2
GR1/3
GR1/4
GR1/5
GR3
GR4
GR5
HA
LA
PR
UT


WEIGHTED
UNWEIGHTED
F_D
T_H
f_c
0.5
0.4
0.3
0.2
0.1
0
0.3
0.2
0.1
0
0.2
0
−0.2
−0.4
WGR
WGR3
GR1/4
WGR1/2
WGR1/4
WGR1/3
GR3
GR1/2
WUT
UT
GR
GR1/5
GR4
WGR4
WGR2
GR2
GR5
GR1/3
WGR5
WGR1/5
GR1/4
GR3
GR1/2
UT
GR
GR1/5
GR4
GR2
GR5
GR1/3

Contributions

- Investigation of centrality metrics to identify key individuals in the spread of COVID-19
- Proposal of a network model considering connections between different age groups
- Development of a more complex COVID-19 propagation model
- Significant reduction in mortality and hospitalizations with strategies based on weighted PageRank

Challenges

- Limitations in the scope of POLYMOD data for different countries and cultures;
- Need to explore the impact of hospital overcrowding in the proposed epidemiological model;
- Evaluation of the effectiveness of vaccination strategies in different epidemiological scenarios;
- Centrality metrics are altered with node removals.