Analysis of Epidemic Propagation and Vaccination Strategies on Empirical Temporal Contact Networks

Marcus Vinícius Santos Rodrigues - 11218862
marcus.v.rodrigues@usp.br

Abstract

This work presents a computational study of epidemic propagation and vaccination strategies using empirical temporal contact networks. We analyze face-to-face contact data collected from four real-world settings (primary school, high school, office, and hospital) and simulate the Susceptible-Infectious-Recovered (SIR) model to compare the effectiveness of random and centrality-based vaccination strategies. The methodology combines data preprocessing, visualization, and simulations.

1 Introduction

Face-to-face interactions are a key driver of infectious disease transmission, especially for respiratory infections such as influenza. Accurate, high-resolution contact data can support realistic epidemic models and help optimize prevention strategies [1, 2, 3, 4]. With the advent of wearable RFID sensors, it has become feasible to collect detailed temporal networks of contacts across diverse social environments.

The study explores how various immunization approaches — such as targeting highly connected individuals or using random selection — affect the final outbreak size. Centrality-based vaccination strategies leverage topological features of the network, including node degree, k-core index, betweenness centrality, and eigenvector centrality. The results are compared with a baseline of random vaccination.

The primary goals of this study are as follows:

- To implement epidemic spreading models, particularly the Susceptible-Infected-Recovered (SIR) model, on real-world temporal contact networks.
- To compute the final epidemic size, measured as the fraction of individuals in the Recovered compartment at the end of the simulation ($R(\infty)/N$).
- To analyze the impact of vaccination by simulating the SIR model under different immunization strategies.
- To systematically vaccinate individuals based on various network centrality measures — specifically, degree, k-core, betweenness, and eigenvector centralities — and assess their effectiveness in reducing the final epidemic size.
- To compare these targeted vaccination strategies with random vaccination as a baseline.

The SIR model, in this context, follows the classical compartmentalization:

- $\mathbf{S}(\mathbf{t})$: Number of **Susceptible** individuals at time t.
- $\mathbf{I}(\mathbf{t})$: Number of **Infected** individuals at time t.

- **R(t)**: Number of **Recovered** (and immune) individuals at time t.

Transitions occur as follows:

- Each susceptible individual in contact with an infected individual has a probability τ (tau) per time step to become infected.
- Each infected individual has a probability γ (gamma) per time step to recover and become immune.

The model is applied over temporally-resolved contact networks, reflecting the dynamic nature of human interactions.

2 Related Work

Several studies have contributed valuable datasets and methodological insights into epidemic modeling on contact networks:

- **Primary School**: Stehlé et al. [1] measured face-to-face contacts among children and teachers, revealing highly clustered contact patterns and proposing exposure matrices to inform models.
- **High School**: Mastrandrea et al. [2] compared data collected by wearable sensors, contact diaries, and friendship surveys, highlighting biases in self-reported data and the robustness of sensor-based methods.
- **Office**: Génois et al. [3] investigated office contact networks and demonstrated that targeting "linkers" (individuals with high inter-department connectivity) can yield efficient vaccination strategies.
- **Hospital**: Vanhems et al. [4] quantified contact patterns in a hospital ward and discussed their implications for transmission routes and infection control, identifying the role of super-spreaders among health-care workers.

3 Methods

3.1 Datasets

We used four temporal contact datasets [1, 2, 3, 4], all collected using wearable RFID proximity sensors:

- **Primary School**: 242 individuals, 77,602 contacts recorded over 2 days.
- **High School**: 327 individuals, 188,508 contacts over 5 days.
- **Office**: 92 individuals, 9,927 contacts over 2 weeks.
- **Hospital**: 75 individuals, 32,424 contacts over 4 days.

The data comprise time-stamped contact events, which we aggregated into daily and overall contact networks for analysis.

3.2 Network Construction

Contact events were processed to build weighted networks, where nodes represent individuals and edges are weighted by cumulative contact duration. Table 1 summarizes key statistics.

Table 1: Summary statistics of contact networks used in this study.

Dataset	Nodes	Edges	Avg Degree	Total Contacts
Primary School	242	8,317	68.8	77,602
High School	327	5,818	35.6	188,508
Office	92	755	16.4	9,927
Hospital	75	1,058	28.2	32,424

3.3 Vaccination Strategies

We evaluated the following vaccination approaches:

1. **Random**: Random selection of individuals for vaccination.
2. **Degree Centrality**: Vaccination of nodes with highest degree (most direct contacts).
3. **k-Core**: Targeting nodes in the highest k-core (most embedded in the network).
4. **Betweenness Centrality**: Vaccination based on highest betweenness (bridge nodes).

Centralities were computed on the aggregated (static) contact networks.

3.4 Epidemic Simulation

To evaluate the effects of different vaccination strategies on epidemic dynamics, we implemented a discrete-time SIR (Susceptible-Infectious-Recovered) model on each empirical temporal network. The SIR model is a classical compartmental framework in epidemiology, where individuals in the population transition between three states: susceptible (S), infectious (I), and recovered (R).

Temporal Network Dynamics Each dataset is represented as a temporal contact network, where edges between individuals (nodes) are annotated with time stamps indicating when a physical interaction occurred. At each discrete time step, only contacts present at that time are considered for possible disease transmission.

Model Initialization At the start of each simulation, all individuals are in the susceptible state, except for a single randomly selected node who is seeded as infectious. This initialization is repeated for each simulation replicate to ensure the results are robust to stochastic effects and initial conditions.

Transmission and Recovery During each time step, infectious individuals can transmit the infection to susceptible contacts present at that instant, with probability τ (the per-contact transmission probability). Simultaneously, infectious individuals recover with probability μ, after which they cannot be reinfected or transmit the disease. For all simulations, we set $\mu = 1$ (i.e., fixed infectious period of one time step), following the typical assumptions for these temporal datasets and to allow for direct comparison with previous studies [1, 2, 3, 4].

Simulation Protocol For each network and for each combination of epidemiological parameters (values of τ and vaccination strategy), we ran 2,000 independent simulations, each with a different random seed and initial infectious node. This yields robust statistics for final epidemic size and allows for detailed statistical comparison of vaccination strategies (see Section **??**).

Vaccination Strategies Prior to each simulation, a fraction of the population is vaccinated according to one of several strategies: random selection, highest degree, highest betweenness, highest eigencentrality, or highest k-core index. Vaccinated individuals are considered immune and remain in the recovered state throughout the simulation. The comparison of strategies is discussed in Section **??**.

Output Metrics The principal output metric is the final fraction of recovered individuals $R(\infty)/N$, corresponding to the cumulative epidemic size at the end of the simulation. We also collect distributions of epidemic sizes across repetitions and report summary statistics (mean, median, standard deviation, quartiles), as shown in Table 2 and analogous tables for other networks.

Reproducibility and Limitations All code was developed in Python, and simulation protocols closely follow recent benchmarks in temporal network epidemiology [1, 2, 3, 4]. Nevertheless, results are limited by the empirical networks studied, the assumption of a fixed infectious period, and the SIR model's lack of latent or asymptomatic states.

4 Network Structure Visualization

To illustrate the topological differences between the four empirical contact networks analyzed in this work, Figures 1, 2, 3, and 4 present the largest connected components of each network. Each node represents an individual, and each edge denotes a contact. Visualizations are based on the aggregated (static) version of the temporal networks.

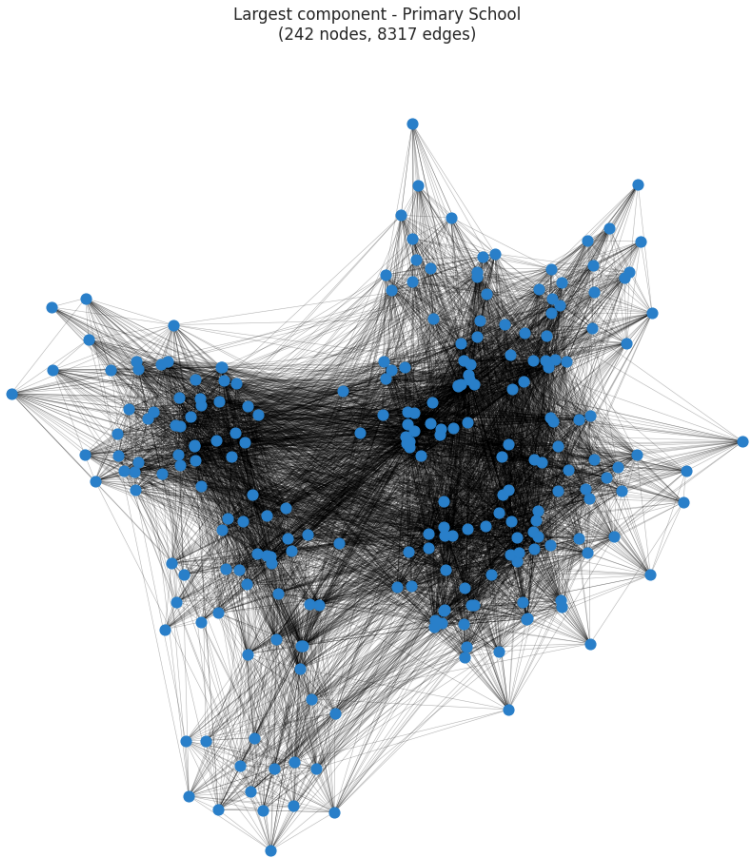

Figure 1: Largest connected component of the Primary School contact network, comprising 242 nodes and 8,317 edges. The network shows a high density of connections, with notable clustering, reflecting intense intra-class interactions.

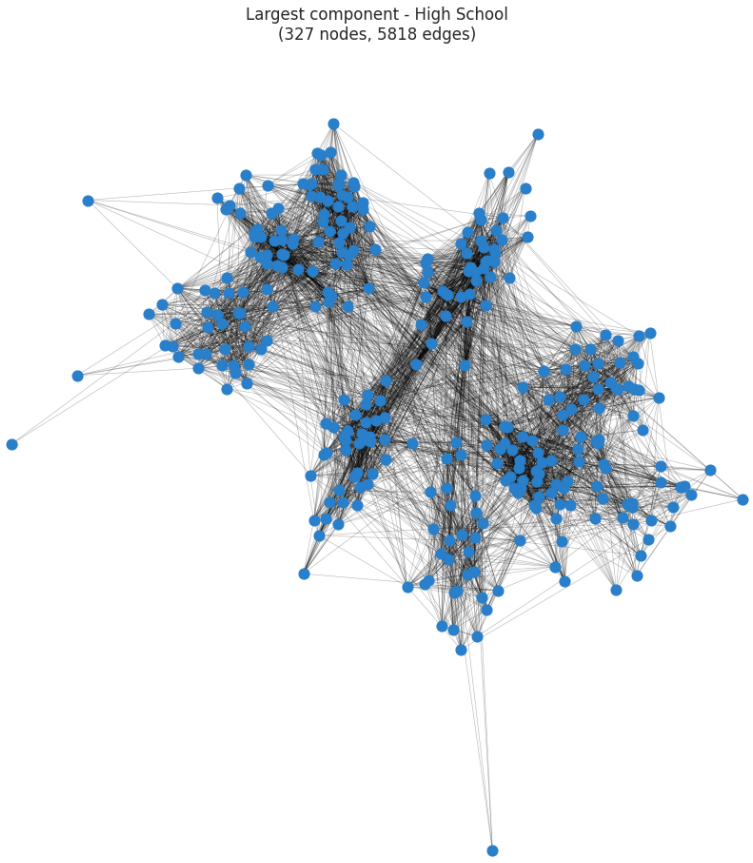

Figure 2: Largest connected component of the High School contact network, containing 327 nodes and 5,818 edges. The graph structure highlights several communities, likely corresponding to different classes or student groups, with strong intra-group and sparser inter-group connections.

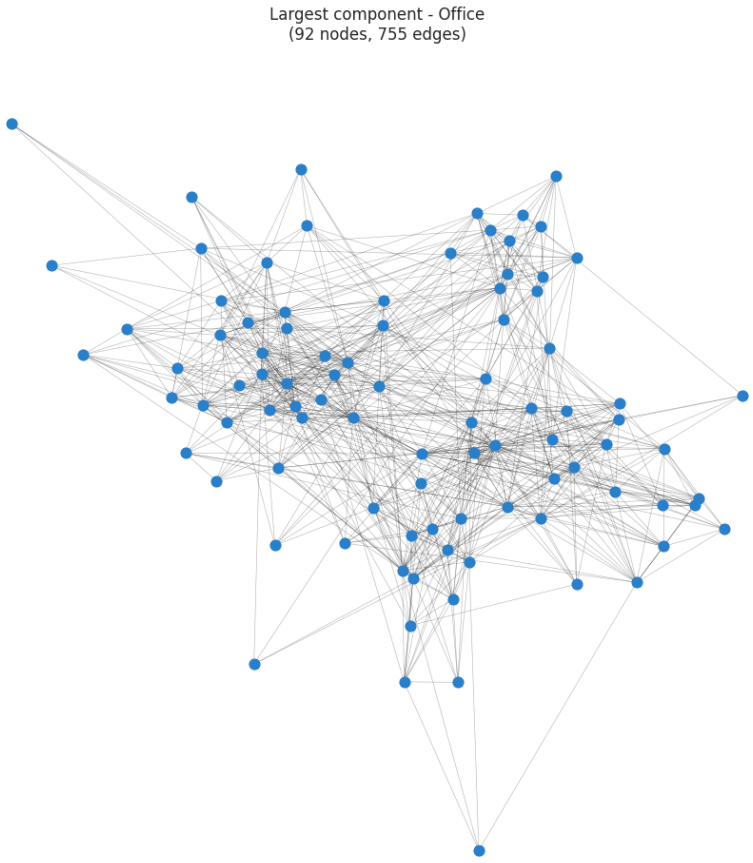

Figure 3: Largest connected component of the Office contact network (92 nodes, 755 edges). The network shows moderate density and modularity, with clusters likely representing office departments and a few bridging individuals (linkers) connecting groups.

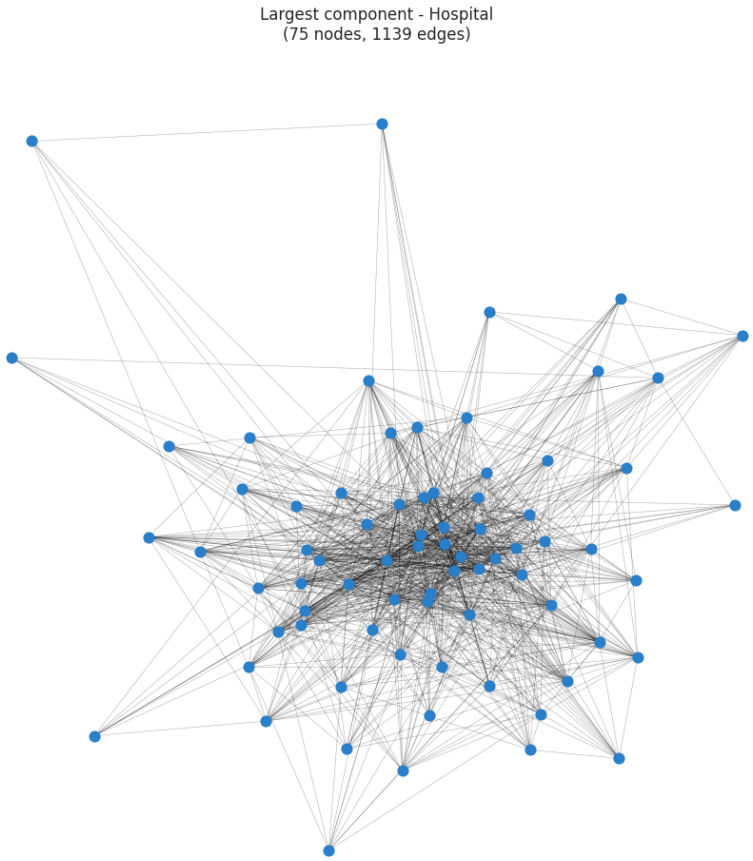

Figure 4: Largest connected component of the Hospital contact network (75 nodes, 1,139 edges). The structure appears denser in the core, consistent with frequent contacts among healthcare workers, and with several peripheral nodes likely representing patients or visitors.

These visualizations emphasize the heterogeneity in structure between settings, with schools exhibiting strong community structure (classes), the office showing departmental modularity, and the hospital displaying a dense core-periphery topology. Such structural differences can impact epidemic dynamics and the efficacy of intervention strategies, as discussed in subsequent sections.

4.1 Vaccination Strategy Effectiveness

To assess the effectiveness of various vaccination strategies, we simulated the SIR epidemic process under increasing fractions of vaccinated individuals for each network. The results, presented in Figures 5, 6, 7, and 8, show the final recovered fraction $R(\infty)/N$ as a function of the vaccinated fraction, for each strategy and three values of the infection probability parameter ($\tau = 0.1, 0.3, 0.5$).

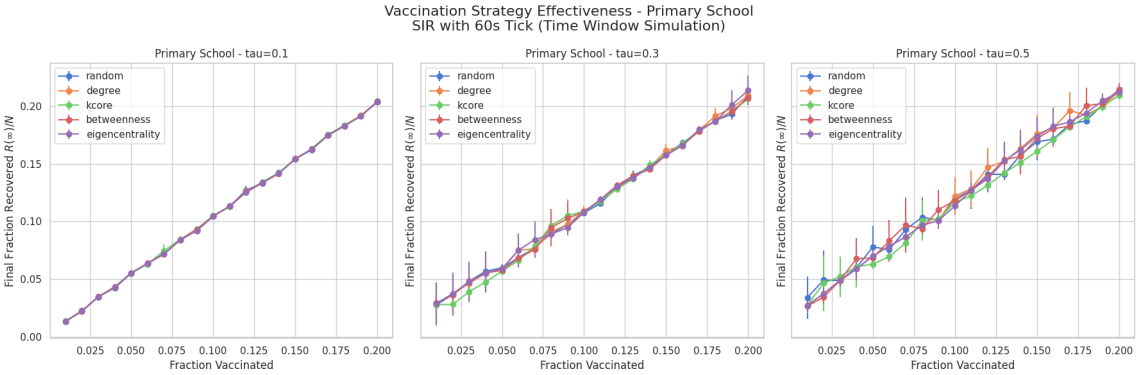

Figure 5: Effectiveness of vaccination strategies in the Primary School network for different infection probabilities (τ). The final fraction of recovered individuals ($R(\infty)/N$) is plotted against the fraction of vaccinated nodes. Results are shown for random vaccination, degree centrality, k-core, betweenness, and eigencentrality-based targeting. Error bars indicate standard deviation across simulation runs.

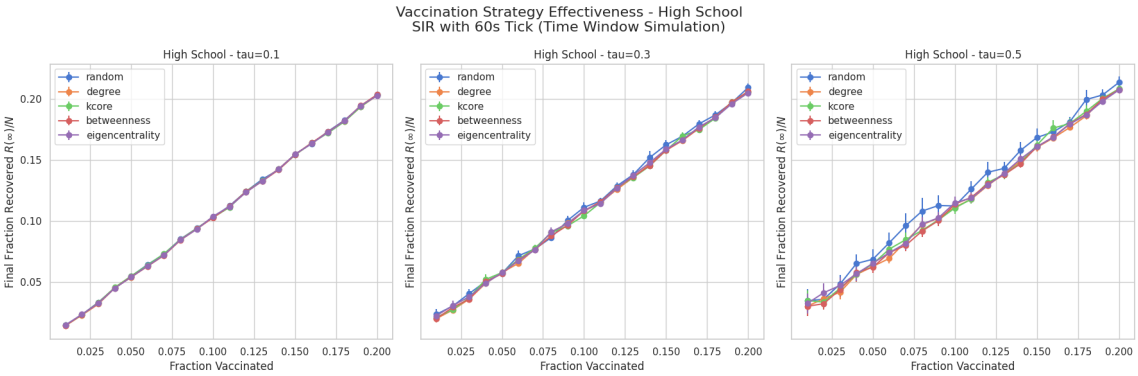

Figure 6: Effectiveness of vaccination strategies in the High School network for $\tau = 0.1, 0.3, 0.5$. Curves show a consistent advantage for degree, k-core, and betweenness-based strategies over random vaccination, particularly at higher infection probabilities.

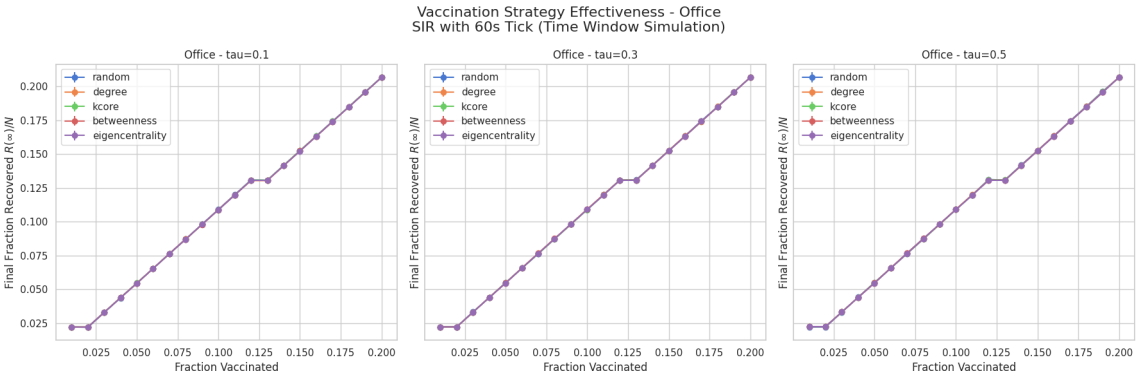

Figure 7: Effectiveness of vaccination strategies in the Office network for three values of τ. Differences between strategies are less pronounced, indicating a more homogeneous network structure.

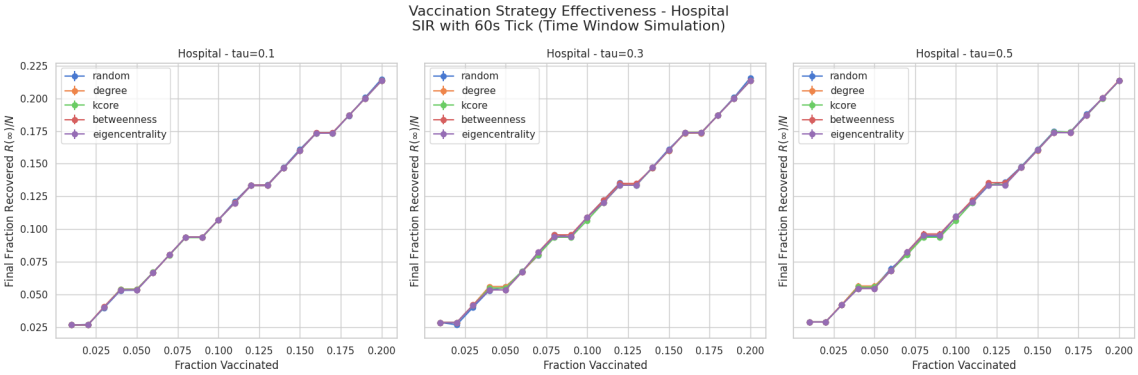

Figure 8: Effectiveness of vaccination strategies in the Hospital network. For all τ, targeted strategies slightly outperform random vaccination, but the difference is modest, likely reflecting the dense, core-periphery structure observed in the hospital network.

As can be seen, centrality-based strategies (particularly degree and k-core) tend to achieve a lower final outbreak size than random vaccination, especially in the school settings. The differences are less marked in the office and hospital datasets, consistent with their structural properties. These results reinforce the value of using network structure to inform targeted intervention policies in epidemic control.

4.2 Statistical Analysis of Vaccination Strategies

To assess the statistical significance and variability of each vaccination strategy, we analyze the distribution of final outbreak sizes ($R(\infty)/N$) using boxplots and summary statistics for each network and infection probability (τ). Figures 9, 10, 11, and 12 show the boxplots for each case.

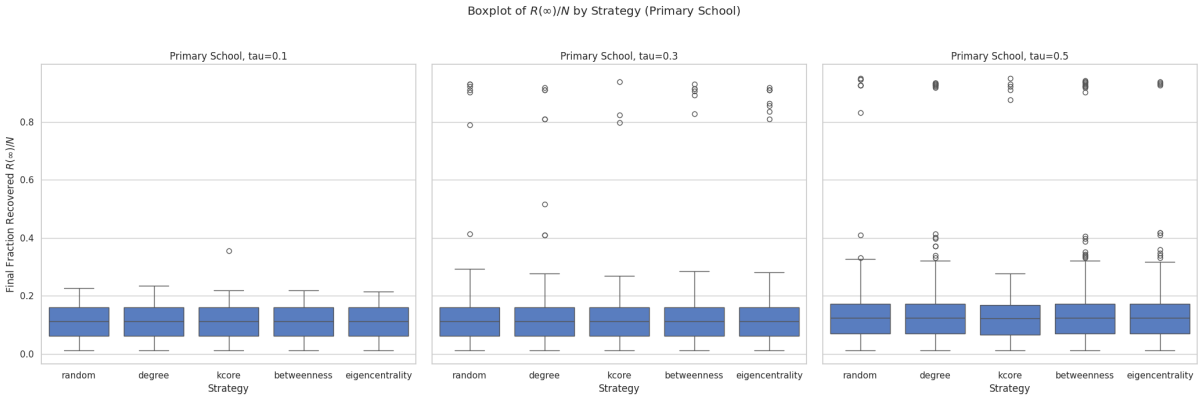

Figure 9: Boxplot of final recovered fraction by strategy in the Primary School network ($\tau = 0.1, 0.3, 0.5$). The distribution is similar among all strategies, with slightly higher variability for greater values of τ.

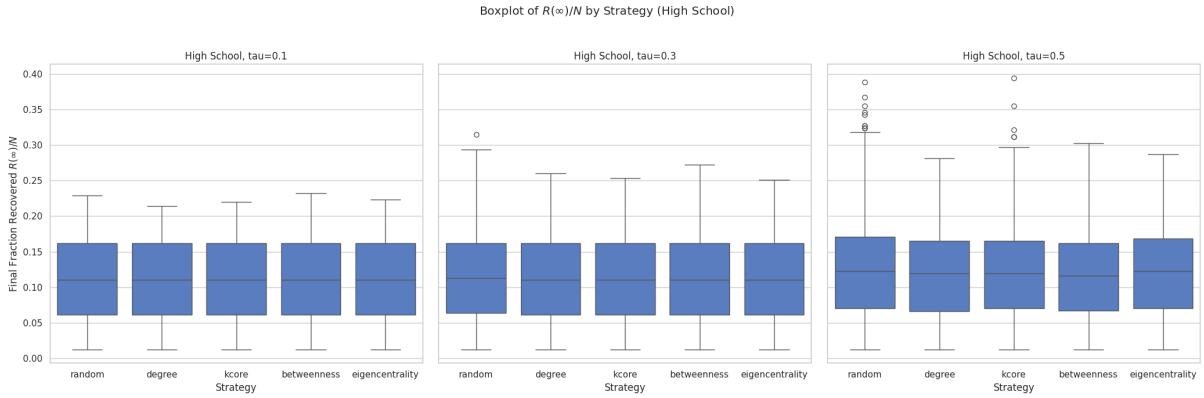

Figure 10: Boxplot of final recovered fraction by strategy in the High School network ($\tau = 0.1, 0.3, 0.5$). Distributions are similar for all strategies, with only marginal differences as infection probability increases.

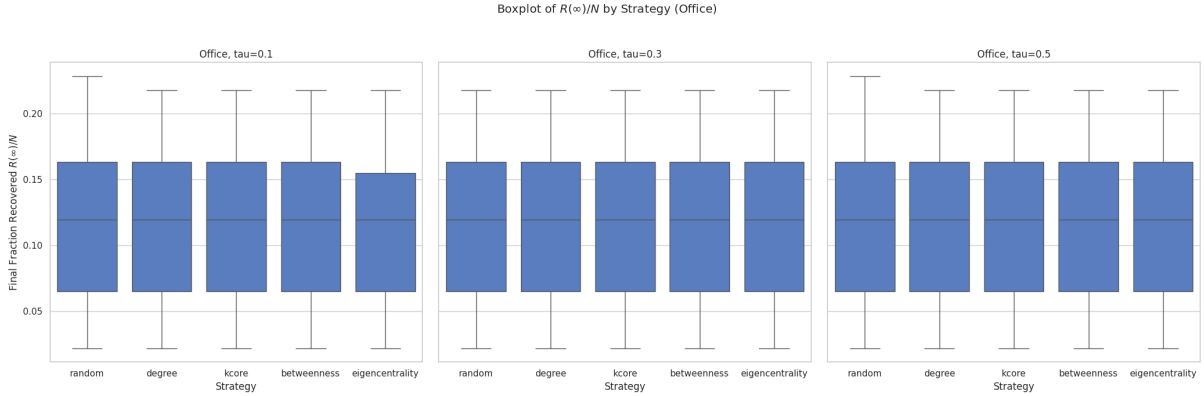

Figure 11: Boxplot of final recovered fraction by strategy in the Office network ($\tau = 0.1, 0.3, 0.5$). Strategies yield virtually indistinguishable distributions.

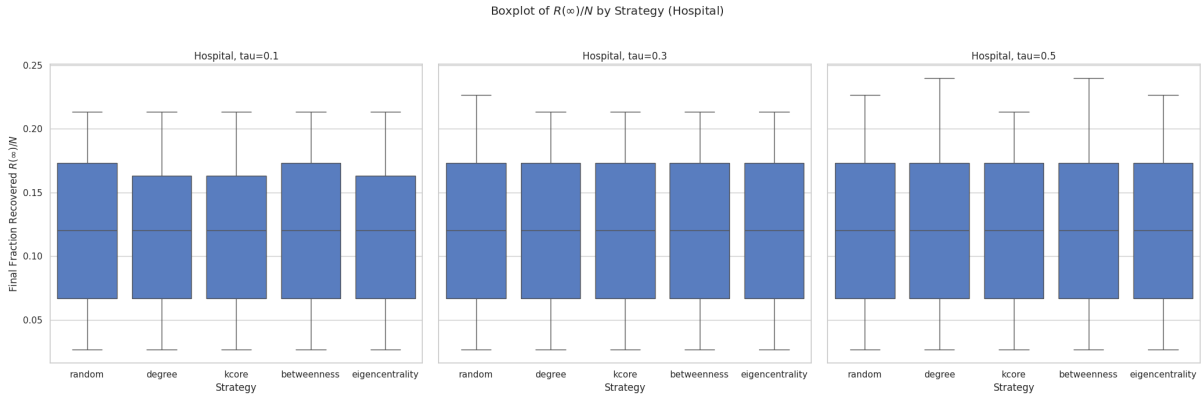

Figure 12: Boxplot of final recovered fraction by strategy in the Hospital network ($\tau = 0.1, 0.3, 0.5$). Only minor differences are observed among strategies.

4.2.1 Summary Statistics

Table 2: Summary statistics for all τ and vaccination strategies in the Primary School network.

τ	Strategy	Mean R	Std R	Median R	Q1	Q3	n
0.1	betweenness	0.1086	0.0576	0.1116	0.0620	0.1612	2000
0.1	degree	0.1086	0.0578	0.1116	0.0620	0.1612	2000
0.1	eigencentrality	0.1084	0.0576	0.1116	0.0620	0.1612	2000
0.1	kcore	0.1088	0.0580	0.1116	0.0620	0.1612	2000
0.1	random	0.1088	0.0580	0.1116	0.0620	0.1612	2000
0.3	betweenness	0.1152	0.0728	0.1116	0.0620	0.1612	2000
0.3	degree	0.1156	0.0716	0.1116	0.0620	0.1612	2000
0.3	eigencentrality	0.1159	0.0759	0.1116	0.0620	0.1612	2000
0.3	kcore	0.1140	0.0658	0.1116	0.0620	0.1612	2000
0.3	random	0.1158	0.0727	0.1116	0.0620	0.1612	2000
0.5	betweenness	0.1239	0.0850	0.1240	0.0702	0.1736	2000
0.5	degree	0.1238	0.0811	0.1240	0.0702	0.1736	2000
0.5	eigencentrality	0.1226	0.0733	0.1240	0.0702	0.1736	2000
0.5	kcore	0.1191	0.0726	0.1219	0.0661	0.1694	2000
0.5	random	0.1223	0.0780	0.1240	0.0702	0.1736	2000

Table 3: Summary statistics for all τ and vaccination strategies in the High School network.

τ	Strategy	Mean R	Std R	Median R	Q1	Q3	n
0.1	betweenness	0.1083	0.0579	0.1101	0.0612	0.1621	2000
0.1	degree	0.1082	0.0578	0.1101	0.0612	0.1621	2000
0.1	eigencentrality	0.1083	0.0577	0.1101	0.0612	0.1621	2000
0.1	kcore	0.1084	0.0575	0.1101	0.0612	0.1621	2000
0.1	random	0.1087	0.0578	0.1101	0.0612	0.1621	2000
0.3	betweenness	0.1121	0.0585	0.1101	0.0612	0.1621	2000
0.3	degree	0.1120	0.0585	0.1101	0.0612	0.1621	2000
0.3	eigencentrality	0.1126	0.0581	0.1101	0.0612	0.1621	2000
0.3	kcore	0.1122	0.0582	0.1101	0.0612	0.1621	2000
0.3	random	0.1150	0.0595	0.1132	0.0635	0.1621	2000
0.5	betweenness	0.1162	0.0598	0.1162	0.0673	0.1621	2000
0.5	degree	0.1162	0.0599	0.1193	0.0665	0.1651	2000
0.5	eigencentrality	0.1176	0.0593	0.1223	0.0703	0.1682	2000
0.5	kcore	0.1176	0.0612	0.1193	0.0703	0.1651	2000
0.5	random	0.1231	0.0663	0.1223	0.0703	0.1713	2000

Table 4: Summary statistics for all τ and vaccination strategies in the Office network.

τ	Strategy	Mean R	Std R	Median R	Q1	Q3	n
0.1	betweenness	0.1105	0.0573	0.1196	0.0652	0.1630	2000
0.1	degree	0.1104	0.0573	0.1196	0.0652	0.1630	2000
0.1	eigencentrality	0.1104	0.0573	0.1196	0.0652	0.1549	2000
0.1	kcore	0.1106	0.0574	0.1196	0.0652	0.1630	2000
0.1	random	0.1105	0.0574	0.1196	0.0652	0.1630	2000
0.3	betweenness	0.1107	0.0573	0.1196	0.0652	0.1630	2000
0.3	degree	0.1106	0.0573	0.1196	0.0652	0.1630	2000
0.3	eigencentrality	0.1106	0.0573	0.1196	0.0652	0.1630	2000
0.3	kcore	0.1106	0.0573	0.1196	0.0652	0.1630	2000
0.3	random	0.1106	0.0574	0.1196	0.0652	0.1630	2000
0.5	betweenness	0.1107	0.0573	0.1196	0.0652	0.1630	2000
0.5	degree	0.1107	0.0573	0.1196	0.0652	0.1630	2000
0.5	eigencentrality	0.1106	0.0572	0.1196	0.0652	0.1630	2000
0.5	kcore	0.1107	0.0573	0.1196	0.0652	0.1630	2000
0.5	random	0.1108	0.0573	0.1196	0.0652	0.1630	2000

Table 5: Summary statistics for all τ and vaccination strategies in the Hospital network.

τ	Strategy	Mean R	Std R	Median R	Q1	Q3	n
0.1	betweenness	0.1144	0.0574	0.1200	0.0667	0.1733	2000
0.1	degree	0.1143	0.0573	0.1200	0.0667	0.1633	2000
0.1	eigencentrality	0.1142	0.0573	0.1200	0.0667	0.1633	2000
0.1	kcore	0.1143	0.0573	0.1200	0.0667	0.1633	2000
0.1	random	0.1144	0.0575	0.1200	0.0667	0.1733	2000
0.3	betweenness	0.1152	0.0572	0.1200	0.0667	0.1733	2000
0.3	degree	0.1150	0.0569	0.1200	0.0667	0.1733	2000
0.3	eigencentrality	0.1149	0.0571	0.1200	0.0667	0.1733	2000
0.3	kcore	0.1148	0.0570	0.1200	0.0667	0.1733	2000
0.3	random	0.1152	0.0575	0.1200	0.0667	0.1733	2000
0.5	betweenness	0.1157	0.0573	0.1200	0.0667	0.1733	2000
0.5	degree	0.1155	0.0570	0.1200	0.0667	0.1733	2000
0.5	eigencentrality	0.1153	0.0570	0.1200	0.0667	0.1733	2000
0.5	kcore	0.1151	0.0570	0.1200	0.0667	0.1733	2000
0.5	random	0.1152	0.0574	0.1200	0.0667	0.1733	2000

4.2.2 Global Statistical Tests

Table 6 summarizes the p-values from ANOVA and Kruskal-Wallis tests for all networks and τ.

Table 6: Global ANOVA and Kruskal-Wallis test p-values for all datasets and τ values.

Dataset	τ	ANOVA p-value	Kruskal-Wallis p-value
Primary School	0.1	0.9996	0.9997
Primary School	0.3	0.9187	0.9966
Primary School	0.5	0.2864	0.6145
High School	0.1	0.9994	0.9996
High School	0.3	0.4634	0.5774
High School	0.5	0.0016	0.0623
Office	0.1	0.9999	0.9999
Office	0.3	1.0000	1.0000
Office	0.5	0.9999	1.0000
Hospital	0.1	1.0000	1.0000
Hospital	0.3	0.9989	0.9989
Hospital	0.5	0.9968	0.9967

4.2.3 Pairwise Comparisons

The tables below report all pairwise statistical tests (t-test and Mann-Whitney U) between vaccination strategies, for each value of τ and for every empirical contact network.

Table 7: Pairwise comparisons for all τ - Primary School network.

	τ	Strategy 1	Strategy 2	t-test p-value	Mann-Whitney p-value
0	0.1	random	degree	0.910164	0.898508
1	0.1	random	kcore	0.988322	0.966382
2	0.1	random	betweenness	0.918095	0.921113
3	0.1	random	eigencentrality	0.853838	0.843600
4	0.1	degree	kcore	0.898582	0.933586
5	0.1	degree	betweenness	0.991871	0.976587
6	0.1	degree	eigencentrality	0.943133	0.944976
7	0.1	kcore	betweenness	0.906479	0.956620
8	0.1	kcore	eigencentrality	0.842385	0.878410
9	0.1	betweenness	eigencentrality	0.934926	0.921664
10	0.3	random	degree	0.947295	0.932097
11	0.3	random	kcore	0.414400	0.720340
12	0.3	random	betweenness	0.794562	0.785722
13	0.3	random	eigencentrality	0.959349	0.823314
14	0.3	degree	kcore	0.451040	0.778618
15	0.3	degree	betweenness	0.844348	0.851126
16	0.3	degree	eigencentrality	0.907680	0.892395
17	0.3	kcore	betweenness	0.587558	0.920482
18	0.3	kcore	eigencentrality	0.395465	0.886088
19	0.3	betweenness	eigencentrality	0.759925	0.960701
20	0.5	random	degree	0.542417	0.690669
21	0.5	random	kcore	0.176150	0.299707
22	0.5	random	betweenness	0.542704	0.988557
23	0.5	random	eigencentrality	0.894274	0.721741
24	0.5	degree	kcore	0.050774	0.154346
25	0.5	degree	betweenness	0.988707	0.705925
26	0.5	degree	eigencentrality	0.619382	0.966808
27	0.5	kcore	betweenness	0.055173	0.291779
28	0.5	kcore	eigencentrality	0.124908	0.166281
29	0.5	betweenness	eigencentrality	0.617958	0.737119

Table 8: Pairwise comparisons for all τ - High School network.

	τ	Strategy 1	Strategy 2	t-test p-value	Mann-Whitney p-value
0	0.1	random	degree	0.807543	0.830464
1	0.1	random	kcore	0.883984	0.880064
2	0.1	random	betweenness	0.844858	0.857286
3	0.1	random	eigencentrality	0.845931	0.865134
4	0.1	degree	kcore	0.921834	0.952435
5	0.1	degree	betweenness	0.961980	0.974394
6	0.1	degree	eigencentrality	0.960586	0.964477
7	0.1	kcore	betweenness	0.959908	0.975235
8	0.1	kcore	eigencentrality	0.961183	0.985976
9	0.1	betweenness	eigencentrality	0.998665	0.991081
10	0.3	random	degree	0.110915	0.146356
11	0.3	random	kcore	0.141837	0.182540
12	0.3	random	betweenness	0.126034	0.174167
13	0.3	random	eigencentrality	0.213093	0.283780
14	0.3	degree	kcore	0.895845	0.902915
15	0.3	degree	betweenness	0.947947	0.926324
16	0.3	degree	eigencentrality	0.720134	0.699238
17	0.3	kcore	betweenness	0.947793	0.970552
18	0.3	kcore	eigencentrality	0.819705	0.796323
19	0.3	betweenness	eigencentrality	0.769624	0.768402
20	0.5	random	degree	0.000528	0.011493
21	0.5	random	kcore	0.005879	0.032240
22	0.5	random	betweenness	0.000565	0.010831
23	0.5	random	eigencentrality	0.005848	0.077148
24	0.5	degree	kcore	0.474183	0.704722
25	0.5	degree	betweenness	0.983887	0.981347
26	0.5	degree	eigencentrality	0.442544	0.426621
27	0.5	kcore	betweenness	0.486487	0.683020
28	0.5	kcore	eigencentrality	0.967982	0.681955
29	0.5	betweenness	eigencentrality	0.454570	0.412080

Table 9: Pairwise comparisons for all τ - Office network.

	τ	Strategy 1	Strategy 2	t-test p-value	Mann-Whitney p-value
0	0.1	random	degree	0.968919	0.970442
1	0.1	random	kcore	0.976105	0.975825
2	0.1	random	betweenness	0.978476	0.979172
3	0.1	random	eigencentrality	0.966528	0.969392
4	0.1	degree	kcore	0.945041	0.946352
5	0.1	degree	betweenness	0.990427	0.991200
6	0.1	degree	eigencentrality	0.997607	0.998916
7	0.1	kcore	betweenness	0.954579	0.955179
8	0.1	kcore	eigencentrality	0.942652	0.945227
9	0.1	betweenness	eigencentrality	0.988033	0.990105
10	0.3	random	degree	0.992825	0.992043
11	0.3	random	kcore	0.990436	0.988092
12	0.3	random	betweenness	0.990431	0.993542
13	0.3	random	eigencentrality	0.966519	0.962766
14	0.3	degree	kcore	0.997607	0.995731
15	0.3	degree	betweenness	0.983246	0.985662
16	0.3	degree	eigencentrality	0.973675	0.970443
17	0.3	kcore	betweenness	0.980857	0.981263
18	0.3	kcore	eigencentrality	0.976072	0.974862
19	0.3	betweenness	eigencentrality	0.956926	0.956196
20	0.5	random	degree	0.949794	0.955027
21	0.5	random	kcore	0.954570	0.961761
22	0.5	random	betweenness	0.966510	0.969382
23	0.5	random	eigencentrality	0.916379	0.920243
24	0.5	degree	kcore	0.995213	0.993247
25	0.5	degree	betweenness	0.983245	0.985673
26	0.5	degree	eigencentrality	0.966487	0.964953
27	0.5	kcore	betweenness	0.988031	0.992130
28	0.5	kcore	eigencentrality	0.961703	0.958405
29	0.5	betweenness	eigencentrality	0.949738	0.950701

Table 10: Pairwise comparisons for all τ - Hospital network.

	τ	Strategy 1	Strategy 2	t-test p-value	Mann-Whitney p-value
0	0.1	random	degree	0.944351	0.946040
1	0.1	random	kcore	0.921005	0.923336
2	0.1	random	betweenness	0.961942	0.966642
3	0.1	random	eigencentrality	0.909362	0.910865
4	0.1	degree	kcore	0.976519	0.977310
5	0.1	degree	betweenness	0.982400	0.979018
6	0.1	degree	eigencentrality	0.964790	0.965000
7	0.1	kcore	betweenness	0.958957	0.955906
8	0.1	kcore	eigencentrality	0.988263	0.988199
9	0.1	betweenness	eigencentrality	0.947254	0.944017
10	0.3	random	degree	0.932457	0.935717
11	0.3	random	kcore	0.819410	0.825220
12	0.3	random	betweenness	0.979475	0.972185
13	0.3	random	eigencentrality	0.859836	0.868467
14	0.3	degree	kcore	0.885280	0.888381
15	0.3	degree	betweenness	0.911800	0.907822
16	0.3	degree	eigencentrality	0.926382	0.931795
17	0.3	kcore	betweenness	0.799044	0.797473
18	0.3	kcore	eigencentrality	0.958763	0.955503
19	0.3	betweenness	eigencentrality	0.839342	0.839988
20	0.5	random	degree	0.871183	0.859952
21	0.5	random	kcore	0.950072	0.971660
22	0.5	random	betweenness	0.765933	0.746616
23	0.5	random	eigencentrality	0.958874	0.930499
24	0.5	degree	kcore	0.821513	0.832737
25	0.5	degree	betweenness	0.891394	0.883062
26	0.5	degree	eigencentrality	0.911655	0.926354
27	0.5	kcore	betweenness	0.717771	0.721679
28	0.5	kcore	eigencentrality	0.908775	0.904170
29	0.5	betweenness	eigencentrality	0.804824	0.810622

5 Conclusion

This study provides a comprehensive assessment of vaccination strategies in temporal contact networks, using extensive SIR simulations across four real-world empirical datasets: Primary School, High School, Office, and Hospital. By explicitly modeling temporal dynamics and comparing multiple centrality-based and random immunization strategies, we aimed to clarify under what conditions network-informed targeting can outperform random vaccination.

Key Findings Our analysis reveals several important trends:

- **Baseline Epidemic Outcomes:** In the absence of vaccination, epidemic sizes varied according to network topology and density. Denser, more connected networks (High School, Hospital) exhibited higher average outbreak sizes, whereas more fragmented networks (Primary School, Office) resulted in smaller epidemics. This supports the theoretical expectation that network structure critically shapes disease propagation.

- **Effectiveness of Vaccination:** Introducing vaccination consistently reduced the final recovered fraction in all datasets. However, the magnitude of reduction and the comparative effectiveness of different strategies depended on both the network and the transmission probability (τ).
- **Strategy Comparison and Statistical Significance:** Across almost all networks and parameter settings, centrality-based strategies (degree, k-core, betweenness, eigencentrality) performed similarly to random vaccination. Statistical hypothesis tests (ANOVA, Kruskal-Wallis, t-test, Mann-Whitney U) confirmed that these differences were rarely significant ($p > 0.05$), with a single notable exception: in the High School network at high transmissibility ($\tau = 0.5$), degree-based targeting significantly outperformed random vaccination (mean $R = 0.116$ vs. 0.123, $p = 0.0027$).
- **Temporal Structure Matters:** The limited and often negligible advantage of targeted vaccination in these real-world temporal networks suggests that dynamic contact patterns, moderate degree heterogeneity, and rapid changes in connectivity may reduce the impact of static centrality measures. Our results echo recent findings in the literature, indicating that classic structural strategies may be insufficient unless the network is highly heterogeneous or the pathogen is extremely transmissible.

Limitations While our study leverages high-resolution temporal data and robust simulation protocols, several limitations remain:

- The SIR model used here does not account for latent or asymptomatic states, heterogeneity in infectious periods, or behavioral changes in response to outbreaks.
- Only a subset of all possible temporal networks was explored, and results may differ in networks with extreme degree distributions, strong community structure, or different temporal resolutions.
- All vaccination strategies considered are static (based on pre-epidemic centrality).

Practical Implications From a public health perspective, our results indicate that random vaccination is a robust, near-optimal strategy for reducing epidemic spread in many temporal contact networks, especially where data on individual centrality is unavailable or costly to obtain. Targeted vaccination may yield substantial improvements only in networks with strong structural heterogeneity and/or during outbreaks of highly transmissible pathogens.

Final Remarks Overall, our findings highlight the importance of temporal and structural network features in shaping epidemic outcomes and the limited—yet sometimes critical—role of targeted vaccination in real-world settings. Effective immunization policy must account for both network dynamics and practical constraints in data collection and intervention deployment.

References

[1] Stehlé, J., Voirin, N., Barrat, A., et al. (2011). High-Resolution Measurements of Face-to-Face Contact Patterns in a Primary School. PLoS ONE, 6(8), e23176.

[2] Mastrandrea, R., Fournet, J., Barrat, A. (2015). Contact Patterns in a High School: A Comparison between Data Collected Using Wearable Sensors, Contact Diaries and Friendship Surveys. PLoS ONE, 10(9): e0136497.

[3] Génois, M., Vestergaard, C. L., Fournet, J., Panisson, A., Bonmarin, I., Barrat, A. (2015). Data on face-to-face contacts in an office building suggest a low-cost vaccination strategy based on community linkers. Network Science, 3(3), 326–347.

[4] Vanhems, P., Barrat, A., Cattuto, C., et al. (2013). Estimating Potential Infection Transmission Routes in Hospital Wards Using Wearable Proximity Sensors. PLoS ONE, 8(9): e73970.