Epidemic Intervention on Dynamic Metapopulation Networks

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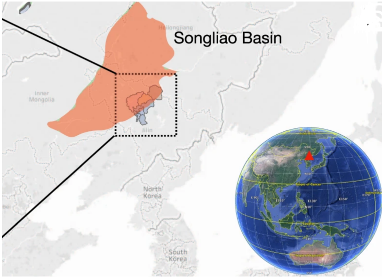
Objectives

- Develop a model that accounts for changes in movement patterns over time, basing the model on realistic movement patterns
- Identify the most optimal vaccination strategy and intervention technique for controlling further spread of an infectious epidemic



Problem

- Without control or preventative measures, localized outbreaks may cause global pandemic
- A limited supply of vaccines
- A limited response window after an outbreak starts

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Mass Action SIR Model

Definition

$S(i)$ is the size of the susceptible population in the ith location. $I(i)$ is the size of the infected population. $R(i)$ is the size of the recovered population.

$$\frac{dS(i)}{dt} = -\beta I(i)S(i)$$

$$\frac{dI(i)}{dt} = \beta I(i)S(i) - \gamma I(i)$$

$$\frac{dR(i)}{dt} = \gamma I(i)$$

R_0

Definition

R_0, the reproductive number, quantifies the outbreak potential of a disease. It is interpreted as the average number of secondary cases generated by a primary case.

$$R_0 = \frac{\beta S}{\gamma}$$

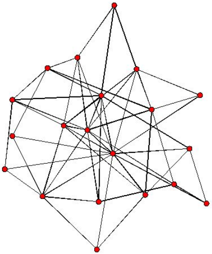
Contact Network Epidemiology

Definition

A *network* is a collection of *nodes* and *edges* between two nodes.

Definition

A *contact network* is a realistic spatial and temporal graph with nodes representing individuals and edges representing the strength of a connection between individuals.



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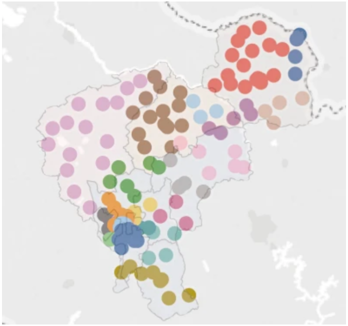
Data

- Sourced from southeast Songliao Basin, Northeast China which span three cities with a total population of 8 million people.
- 70 million movements from 3 million cellular devices
- 167 administrative districts
- Hourly changes in location are recorded for every individual for 1 week



Flow Matrices

Definition

We define flow matrix F as $F^t = [F^t_{i,j}]^n_{i,j=1}$, where entry $F^t_{i,j}$ represents the number of people traveling from node i to j within a given time period, t. We divide the week into 21 8-hour blocks for t.

$$
\begin{array}{c c}
 & \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} \\
\begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} &
\begin{pmatrix}
0 & 1 & 3 & 1 & 1 \\
1 & 0 & 1 & 1 & 1 \\
2 & 1 & 0 & 1 & 1 \\
1 & 2 & 1 & 0 & 0 \\
1 & 1 & 1 & 0 & 0
\end{pmatrix}
\end{array}
$$

Simulation Dynamics

When a person is vaccinated, they are no longer susceptible to disease, so they are moved from the susceptible compartment to the recovered compartment. We use two equations each to determine $S_i(t), I_i(t)$, and $R_i(t)$; the first to account for internal changes, the second to account for in and out migration.

$$S_i'(t+1) - S_i(t) = -\frac{\beta S_i(t) I_i(t)}{N_i(t)} \tag{1}$$

$$S_i(t+1) - S_i'(t+1) = \sum_{j=1}^{L} \frac{F_{j,i}^{t \pmod P} S_j'(t)}{N_j(t)} - \sum_{j=1}^{L} \frac{F_{i,j}^{t \pmod P} S_i'(t)}{N_i(t)}$$

Simulation Dynamics

(2)
$$I_i'(t+1) - I_i(t) = \frac{\beta S_i(t) I_i(t)}{N_i} - \gamma I_i(t)$$

$$I_i(t+1) - I_i'(t+1) = \sum_{j=1}^{L} \frac{F_{j,i}^{t \pmod P} I_j'(t)}{N_j(t)} - \sum_{j=1}^{L} \frac{F_{i,j}^{t \pmod P} I_i'(t)}{N_i(t)}$$

(3)
$$R_i'(t+1) - R_i(t) = \gamma I_i(t)$$

$$R_i(t+1) - R_i'(t+1) = \sum_{j=1}^{L} \frac{F_{j,i}^{t \pmod P} R_j'(t)}{N_j(t)} - \sum_{j=1}^{L} \frac{F_{i,j}^{t \pmod P} R_i'(t)}{N_i(t)}$$

(4)
$$N_i(t) = S_i(t) + I_i(t) + R_i(t)$$

Model Parameters

Parameter	Description	Value
T	length of simulation in 8-hour time steps	42
P	total number of time steps in data	21
L	total number of locations	167
β	transmission rate	1.55
γ	recovery rate	0.19
R_0	basic reproduction number	7.8
N	total population in all locations	8,000,000

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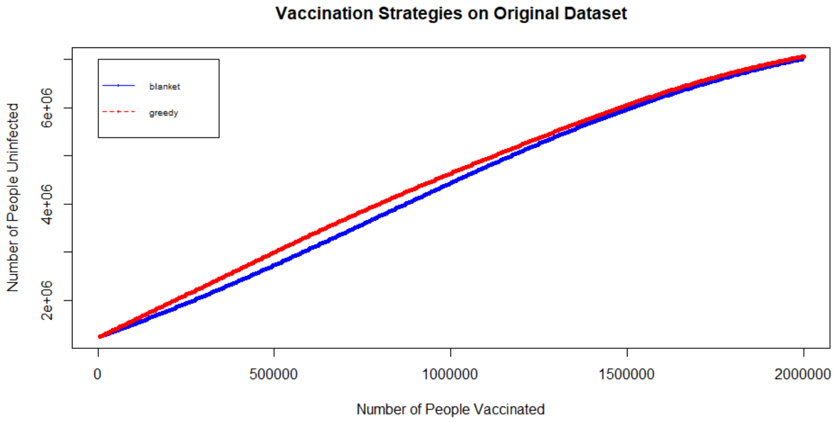
Interventions

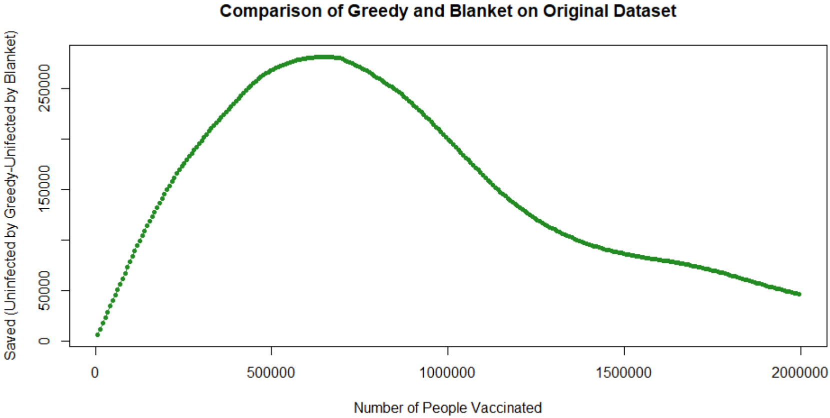
We proposed 2 intervention measures:

1. **Blanket**: If the vaccine availability is $x\%$ of the population, then vaccinate $x\%$ of the population at each location.
2. **Greedy Algorithm**: We aim to find the locally optimum location to vaccinate a person after each iterative step of vaccination. We repeat this process until the vaccine availability is depleted.

Interventions



Interventions

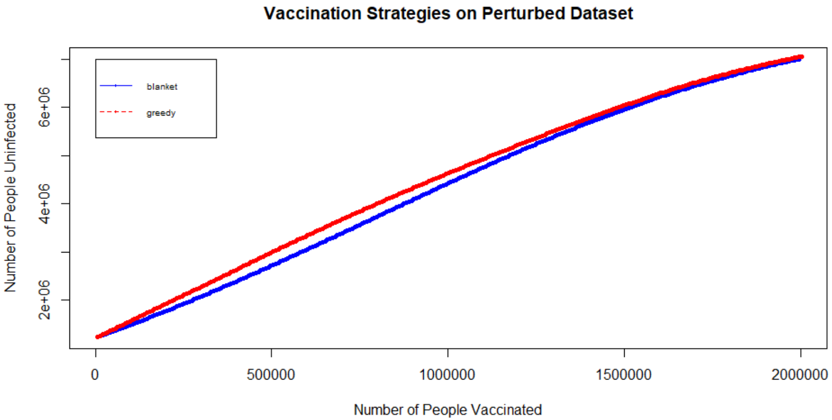


Interventions

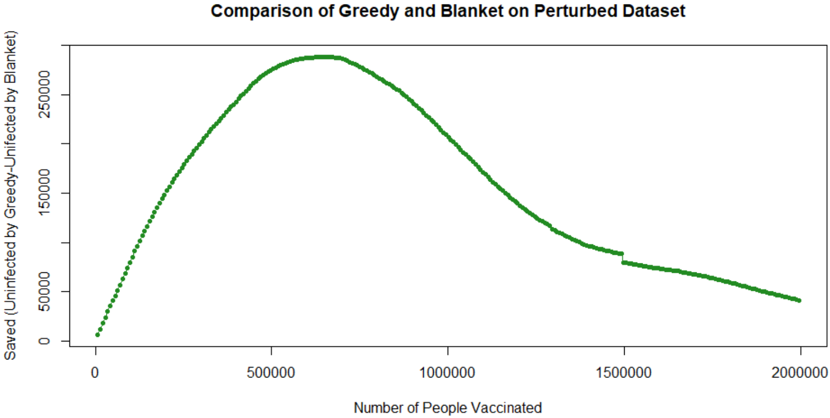
- To verify that our strategy was not hyper sensitive to the exact data set, we perturbed the data to perform a sensitivity test.
- We define the transformation as follows, where *rnorm* is a random number generator with a Normal, or Gaussian, distribution.

$$F'^{\,t}_{i,j} = rnorm(\mu = F^t_{i,j}, \sigma = F^t_{i,j}/6)$$

Interventions



Interventions



Conclusion

- Greedy Algorithm for vaccination is the more effective vaccination strategy to arrest the transmission of a potential outbreak compared to the commonly used blanket strategy on both the original and perturbed data sets.
- In the future, we would like to test hybrid vaccination strategies and explore the cost-effectiveness of each vaccination strategy.

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