Realistic Modeling and Simulation of Influenza Transmission Over an Urban Community

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Introduction

The spread of infectious diseases is influenced by the particular configuration of links among individuals in local communities within the larger population. Traditional SIR models do not take into account the spatio-temporal variability and complex structure of interpersonal connections. Here we study the transmission of influenza using a realistic population model. These kinds of models make it possible to monitor the progression of the disease and devise and test possible intervention strategies. Typically, about 15% of adults are vaccinated from a community. We use this knowledge to implement a realistic vaccination strategy which calms the spread of infection.

Model

The model:
- comprises 245,809 individuals located in an urban area in the Northeastern United States;
- is based on 2010 Census data combined with commercially available user data;
- is three-partite temporally: daytime, pastime, nighttime;
- is three-partite spatially: home, workplace, service place locations.

Table 1: Average size of home and workplace locations

Location:	Home	Daytime Workplace	Pastime Workplace
Average Number of Individuals at a Location:	2.4	5.2	1.9

Daytime Population

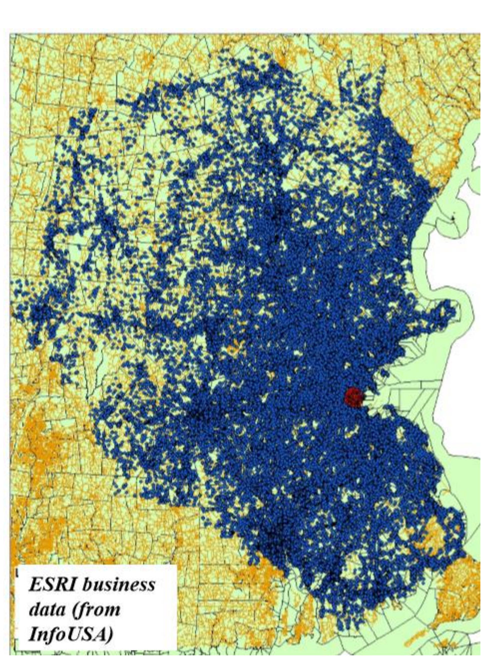


Table 2(a): Percent of population at each location – WEEKDAY

WEEKDAY	At home	As employee at work (may be at service location)	As customer at service location
Daytime	22.5 %	72.7 %	4.8 %
Pastime	78.2 %	4.4 %	17.4 %
Nighttime	100.0 %	0.0 %	0.0 %

Table 2(b): Percent of population at each location - WEEKEND

WEEKEND	At home	As employee at service location	As customer at service location
Daytime	73.0 %	5.0 %	22.0 %
Pastime	93.0 %	3.8 %	3.2 %
Nighttime	100.0 %	0.0 %	0.0 %

Methods

- 500 Monte-Carlo simulations were performed of the spread of influenza through the network for each model.
- Regular contacts between family members and coworkers; casual contacts between customers and service employees.
- Each individual can be one of four statuses:
  - **Susceptible**: can contract the disease if in contact with an infectious individual
  - **Latent**: has already contracted the disease, but cannot yet infect others (latent period is 2 days)
  - **Infectious**: infected individual who can spread the disease by contact with susceptible individuals (infectious period is 8 days for children and 5 days for adults and seniors)
  - **Recovered**: individual is no longer infectious and is immune to the disease for the rest of the simulation.
- Disease was allowed to spread for 1000 days.
- One random employee contracts the disease and instigates the outbreak.

Table 3: Infection rates for disease transmission

Adults	Children	Seniors
5%	3%	5%

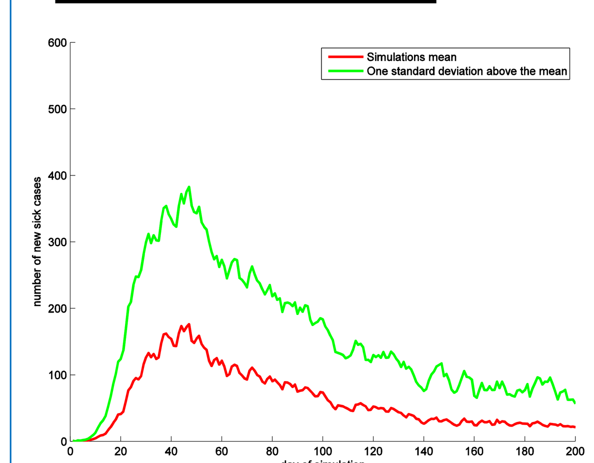
Model Variants

Several variants of the model were examined:

1: Everyone starts out susceptible
2: Random 15% of population is chosen to be vaccinated
3: Specifically chosen 15% of population with the highest number of contacts vaccinated
4: Realistic hypothetical case – vaccination stations are set up in all educational institutions. Random 15% of individuals who work at educational institutions are vaccinated

*The same number of people were vaccinated for models 2, 3, and 4.

Simulations



- **Validation:** The trend of newly infectious cases agree well with actual infection data from CDC. Both demonstrate a bell curve-like shape as shown on the left.
- Vaccinating a targeted 15% of the population (model 3) significantly decreases the progression of infection.
- Vaccinating specifically in educational institutions reduces the affect of the disease (model 2 vs. model 4).
- Infections affect either less than 2,000 individuals or more than 4,000 individuals for all model variants → we can use 2,000 individuals as a benchmark in monitoring the spread of infection.
- Most infections occur at home → focus prevention strategy on contacts between family members.

Location where infections occur:

We can compute the relative numbers of transmissions occurring at home, workplace, and service places.

Method 1:

$$T = \sum H_i + \sum W_i + \sum S_i$$

$$\%\,Home = \frac{\sum H_i}{T};\ \%\,Work = \frac{\sum W_i}{T};\ \%\,Service = \frac{\sum S_i}{T}$$

Method 2:

$$T_i = H_i + W_i + S_i$$

$$\%\,H_i = \frac{H_i}{T_i};\ \%\,W_i = \frac{W_i}{T_i};\ \%\,S_i = \frac{S_i}{T_i}$$

$$\%\,Home = average(\%\,H_i);$$
$$\%\,Work = average(\%\,W_i);$$
$$\%\,Service = average(\%\,S_i);$$

where H_i is the number of infections spread at home, W_i is the number of infections spread at the workplace, and S_i is the number of infections spread by interactions with a customer at a service place for simulation i.

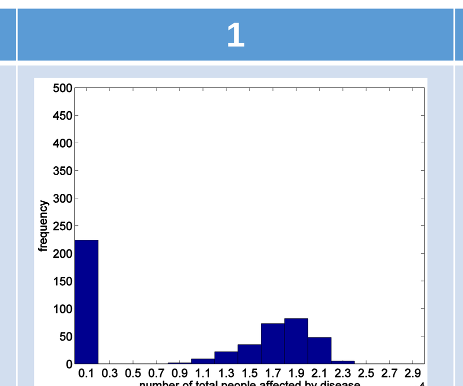
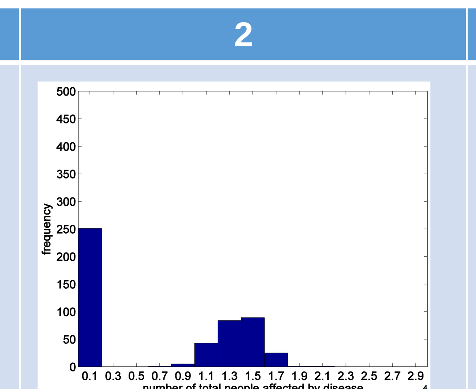
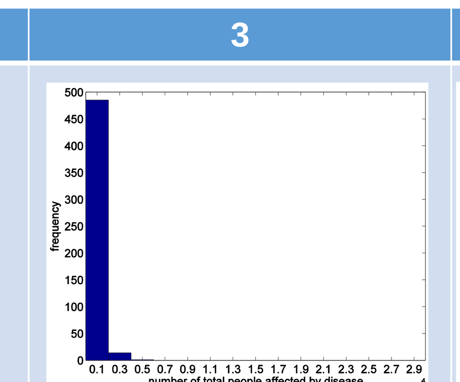
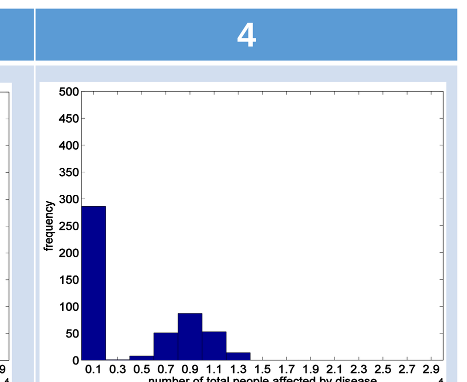
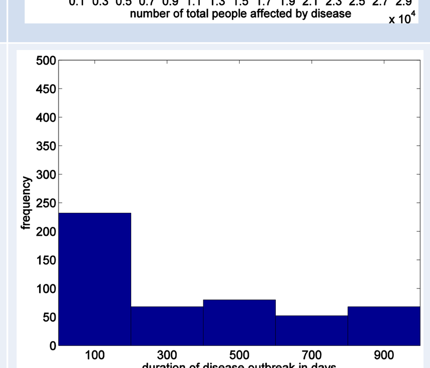
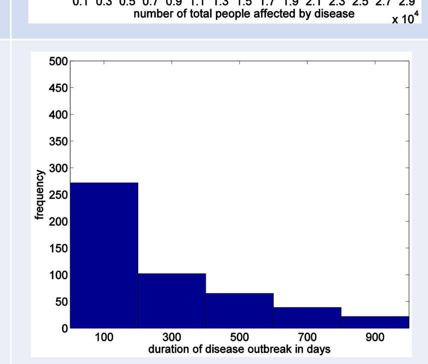
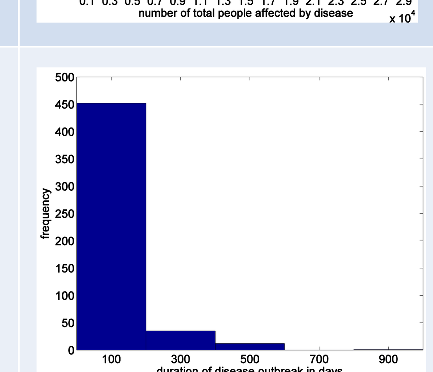
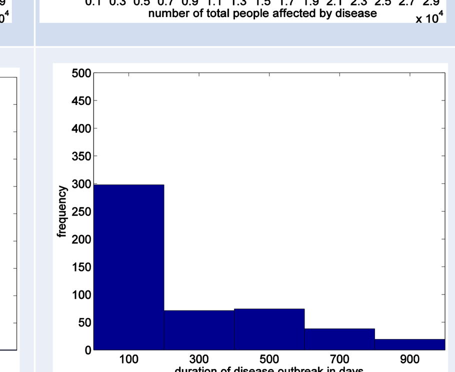
Table 4(a): Location of Infection - Method 1

Model	Home	Workplaces	Service place (customer)
1	83.9 %	15.9 %	0.2 %
2	86.8 %	13.1 %	0.1 %
3	47.1 %	52.6 %	0.3 %
4	82.3 %	17.5 %	0.2 %

Table 4(b): Location of Infection - Method 2

Model	Home	Workplace	Service place (customer)
1	76.8 %	23.0 %	0.2 %
2	75.3 %	24.3 %	0.4 %
3	48.1 %	51.1 %	0.8 %
4	71.4 %	28.3 %	0.3 %

Table 5: Simulation results for model variants 1 – 4

Model	1	2	3	4
Frequency of runs vs. Total number of individuals affected by disease				
Frequency of runs vs. Duration of disease				

Future Work

We expect that the findings will offer a platform to devise spatially and temporally oriented intervention strategies for communicable diseases.

References

1. L. Bian, et al.: "Modeling Individual Vulnerability to Communicable Diseases: A Framework and Design". *Annals of the Association of American Geographers* **102** (5):1016-1025 2012
2. M.E.J. Newman: *Networks* (Oxford University Press, 2010)