Agent-Based Model (ABM) for Epidemiological Spread: Urban and rural environments

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Research question:

How do the factors of movement, vaccination rate and environment interact to impact the spread of disease?

Why?

- Importance of understanding disease dynamics to inform public health strategies and interventions.
- Relevance in simulating real-world disease responses, such as reactive vaccination strategies during outbreaks.
- Movement is represented by distance and speed that an individual goes through their environment, while environment represents the boundaries of a city/area in which individuals stay
- Modeling can reveal how factors like age, movement, and density affect transmission, allowing for tailored strategies, such as targeting specific age groups or high-density areas.

Variables of interest:

Age: determines movement patterns, which determines how frequently agents move in environment
Vaccination Rates: Proportion(%) of agents who are vaccinated in a population of susceptible agents
Environmental Setting: Urban (high-density) vs. rural (low-density) areas.

Background

3 Subtopics, which the model was based on:

- ABMs in epidemiology
- Disease dynamics in different environments
- Vaccination strategies

Agent-Based Models (ABMs) in Epidemiology

Customization of parameters

- Able to easily customize parameters and variables to suit specific goals.
- ABMs show flexibility by capturing spatial elements like movement within an environment.(Alaliyat & Yndestad 2015)

Reality based

- ABM's are able to incorporate real time factors and track outcomes
- Incorporating factors like age and movement in disease spread helped simulate disease spread (Hunter, Mac Namee, & Kelleher 2018)

Versatility of modeling

- ABMs help identify the most effective strategy based on factors like population connectivity, vaccine availability, and the timing of interventions
- ABMs can represent disease spread across diverse population structures and settings, representing heterogeneity(Azman & Lessler 2015)

Why this supports our research question?

- ABMs capture diverse population characteristics like age and movement in different settings.
- They allow us to examine interactions in urban vs. rural contexts, key to our study.
- The ability to integrate vaccination rates and movement dynamics makes ABMs ideal for our focus on disease spread.
- ABMs provide insights into tailored intervention strategies, helping us model responsive public health approaches.

Disease Dynamics in Different Environments

Rural Areas and Public Health Challenges:

- Rural areas often face challenges in public health knowledge and vaccine hesitancy, which can exacerbate disease spread
- Important to understand how these factors interact with population density, mobility, and vaccination rates in influencing disease transmission.
- Initially, COVID-19 incidence was higher in urban areas, but rural areas eventually saw significant increases.(Cuadros & Branscum (2021))
- Rural areas have higher death rates and unique challenges that can increase preventable deaths.(Moy et al.,2017)

Relevance to Research Question:

- Rural areas display limited public health knowledge
- Highlights importance of population density and connectivity in rural areas
- he challenges faced by rural areas, particularly with vaccination rates and healthcare access, can significantly alter disease dynamics. This makes it important to consider these variables in modeling disease spread.

Vaccination Strategies and Disease Control

Reactive vaccination

- Reactive vaccination strategies are shown to be effective in disease hotspots
- Timing of the intervention can significantly impact the spread of disease
- (Grais et al., 2006)

Vaccination Strategies

- Vaccination plays a critical role in mitigating disease spread by building immunity within populations.
- By incorporating vaccination strategies in the ABM, we can model how vaccines slow the transmission of diseases.
- Shown in previous studies(Maziarz and Zach, 2020)

ABMs and disease control

- ABMs can be used to simulate the effects of intervention of Covid vaccines.
- Additional methods such as masks and social distancing can also feasibly be modeled
- (Philip Ciunkiewicz et al., 2022)

Why this supports our research question?

- Allows our ABM to be more accurate and represent real life scenarios.
- Both vaccines and disease control are major factors in the spread of a disease.
- Our ABM can stay up to date on new medical advancements in real time.

Why an ABM?

- ABM is ideal because it captures differences within populations and allows each agent to act independently based on specific attributes and interact spatially.
- ABMs can adjust variables like vaccination thresholds and movement rates, allowing the model to simulate responsive strategies and show different interventions affect disease outcomes.
- ABMs allow for the exploration of reactive vaccination strategies which help to assess which strategies are most effective under various conditions.
- Can run model multiple times to observe common trends

Model overview

How do the factors of movement, vaccination rate and environment interact to impact the spread of disease?

Variables of interest:

Movement patterns:

- Refers to the frequency and direction in which agents (individuals) move.
- Movement likelihood affected by age (younger: higher probability to move and change direction).

Vaccination rates:

- The proportion of agents that are vaccinated based on infected threshold.
- Vaccination will be applied in response to the amount of infected individuals.

Environmental Setting:

- Refers to whether the agents are located in urban (high-density) or rural (low-density) areas.
- The parameters gridSize and gridHeight set the boundaries in which agents move based on the density of their area.

Overall:

- Agents represent individuals with age-based movement and vaccination status, moving and interacting on a 2D grid.
- The model accounts for different population densities.
- Disease transmission occurs when susceptible individuals come in contact with infected ones.
- Vaccination takes place when an infected threshold is reached.
- By adjusting population density, movement rates, and vaccination triggers, the model represents several different scenarios, each with specific intervention strategies.

Methods section

Entities

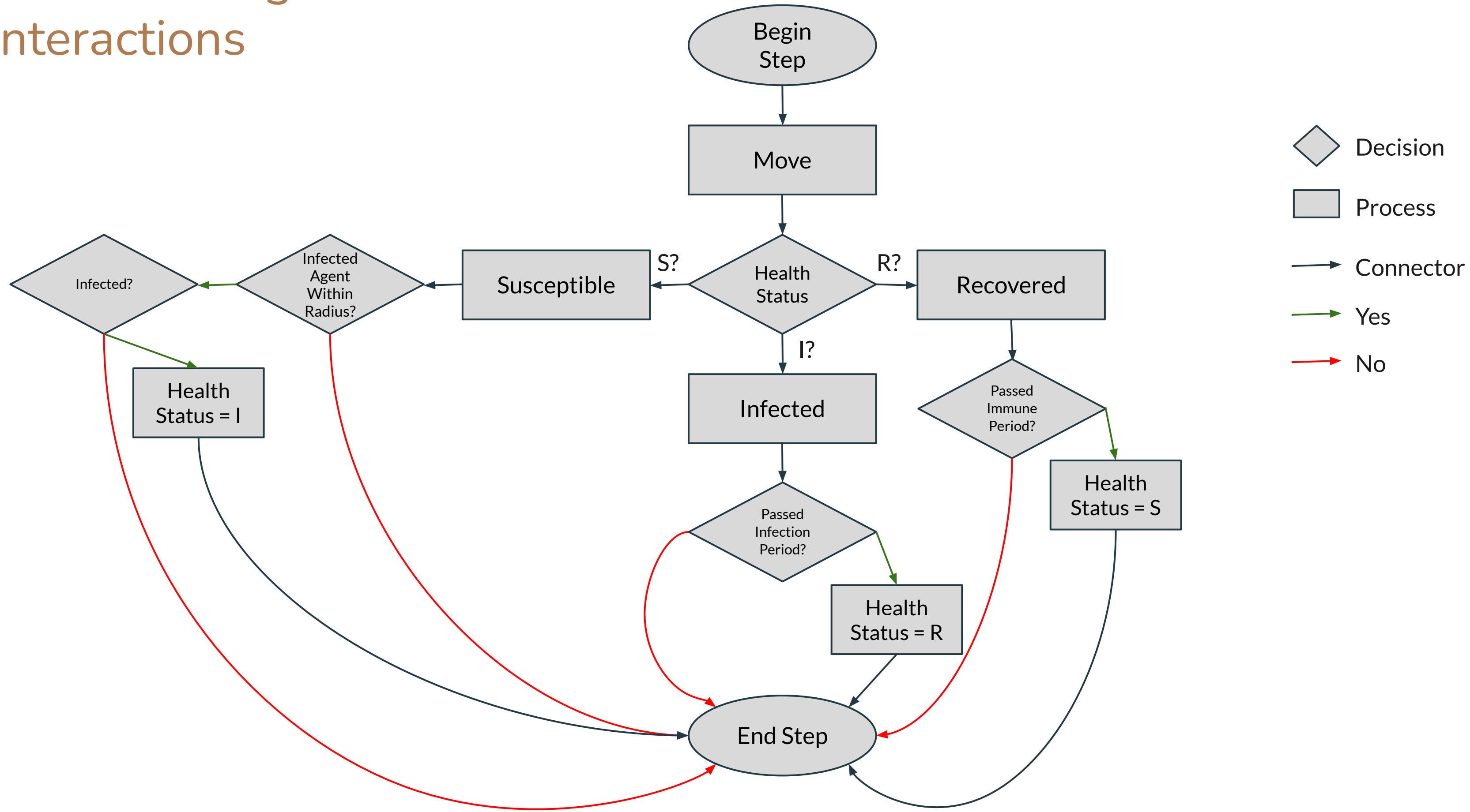
Agent: Characteristics	Internal upkeep
Age(Young 7-65, Old 65+)	None
Health status:Susceptible, Infected, Recovered	Keep track of health status, can change based on interactions between agents
Vaccination status(Vaccinated/not vaccinated)	Can change based on vaccination policy
X,Y	Changing based on movement keeps track of agent
Xdir,Ydir	Changing based on movement which is dependant upon age,

Environment: Characteristics
gridSize and gridWidth

Rationale:

- Age 65+ represents age of retirement. Retired individuals tend to be less mobile
- Reflects real-world differences in disease transmission based on age and environment.
- Previous ABM models utilize SIR model to simulate age and disease spread(Namee, Kelleher, Hunter 2018)

Decision Diagram and interactions



Virtual experiments

Parameter	Default values	Explanation/Rationale
# of older/younger agents	50/50	• An equal split of older and younger agents ensures balanced comparisons in infection dynamics across age groups. (Hunter et al., 2019)
Pinfection(constant)	0.3	• A moderate infection probability balances between overly rapid and slow spread, reflecting disease like COVID-19 (Philip C. et al., 2022)
Infection duration	50 steps	• Represents diseases with a medium infection duration, gives opportunity for disease spread before immunity kicks in.
GridHeight,GridWidth	50x50	• Setting boundaries for space representing environment. Urban areas have higher connectivity, justifying a smaller grid size. (Cuadraos et al., 2021)
# of agents needed to trigger vaccinations	10	• Default value of 10 since it would be about 10 percent of the population of agents, modeling early vs late vaccination intervention. (Azman et al., 2015)
# of agents who become vaccinated(constant)	20	• 20% of population ensures a measurable effect of vaccination without completely stopping spread. Previous studies showed 20-30 percent of vaccination at the end (Azman et al., 2015)
Infection radius(constant)	1 block	• Default value of 1 to represent an infected agent spreading disease within a close radius. Previous studies used smaller radius to represent close radius (Alaliyat et al., 2015)
Immunity duration(constant)	100 steps	• Immunity duration is double the infection duration. Alaliyat and Yndestad (2015) highlighted that immunity loss affects disease dynamics cycles

Hypotheses

Research Question: How do movement, vaccination rate, and environment interact to impact disease spread?

Hypotheses:

- 1. Decreasing older agents increases total infections.
- 2. Changing the environment from urban to rural lowers total infections.
- 3. Increasing infection duration raises the total number of cases over time.
- 4. Decreasing the number of infections needed to trigger vaccinations, will decrease the number of infected agents over time.

Justification: These 4 hypotheses fit together to model movement, vaccination rate, and environment and we can see how each one affects the disease spread based on the results of testing these.

Parameter sweep

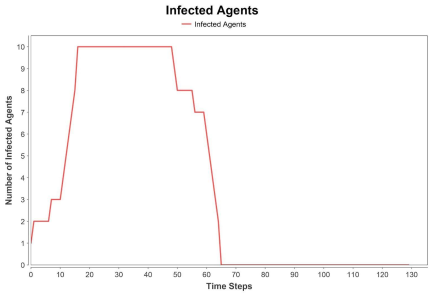
Parameter	Test 1	Test 2	Test 3	Test 4
# of older agents/# of younger agents	50/50, 20/80	50/50	50/50	50/50
PInfection	0.3	0.3	0.3	0.3
Infection duration	50 steps	50 steps	50,100 steps	50 steps
GridHeight, GridWidth	50x50 150x150	150x150,50x50	50x50 150x150	50x50 150x150
# of infected agent needed to trigger vaccinations	10	10	10	10/30
# of agents who become vaccinated	20	20	20	20
Infection radius	1 block	1 block	1 block	1 block
Immunity duration	100 steps	100 steps	100 steps	100 steps

- Hypothesis 1 is tested by decreasing number of older agents and replacing with younger agents.
- Hypothesis 2 is tested by comparing 800x800 to 300x300 to represent rural vs urban.
- Hypothesis 3 is tested by comparing 50 vs 100 steps of infection duration.
- Hypothesis 4 is tested by comparing 6 to 10 number of agents needed to trigger vaccination.

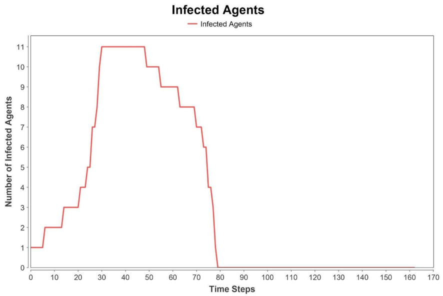
Results

Test 1: Concrete hypothesis: **Decreasing older agents increases total infections**

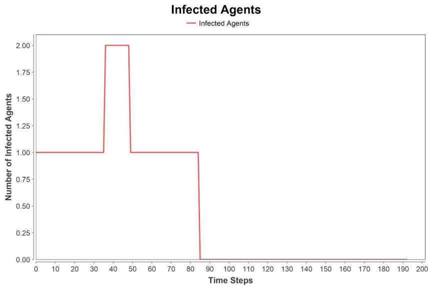
Graph 1: 50/50 older/younger agents in Urban environment



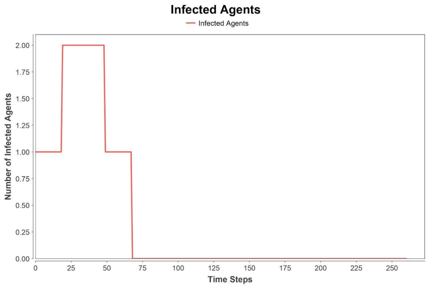
Graph 2: 20/80 older/younger agents in Urban environment



Graph 3: 50/50 older/younger agents in a rural environment



Graph 4: 20/80 older/younger agents in Urban environment



Explanation:

- Reduced mobility limits older agents' role in the disease transmission chain.
- Younger, more mobile agents encounter more individuals, increasing their potential for spreading the disease.
- Aligns with prior research indicating that movement facilitates the spread of infectious diseases.
- **Parameter Swept:** Age parameter was varied to test its impact on disease transmission dynamics.

Observations:

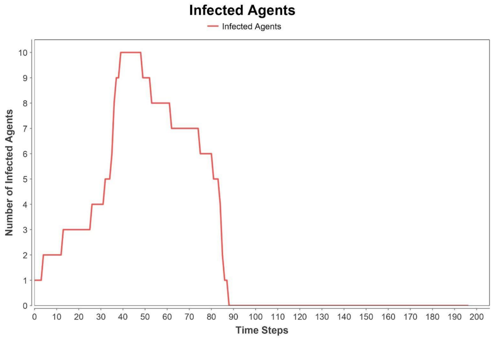
- The primary effect of varying the age distribution is on the duration the model stays at the peak infection level.
- Total infections remain similar across all scenarios, regardless of the ratio of younger to older agents.

Conclusion:

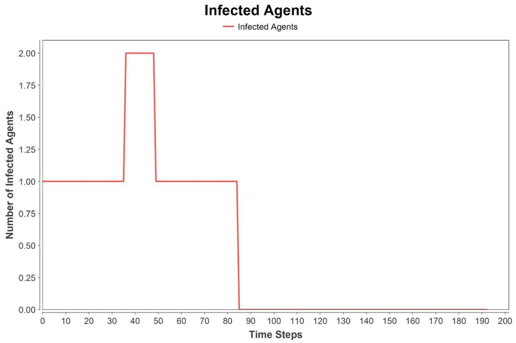
- Data does not provide strong evidence to conclude that decreasing the number of older agents increases total infections.
- Similar numbers of infected agents were observed in both urban and rural comparisons.

Test 2: Concrete hypothesis: **Changing the environment from urban to rural lowers total infections.**

Graph 1: Urban environment



Graph 2: Rural environment



Explanation:

- Urban areas have higher population density, leading to more interactions between susceptible and infected agents.
- Rural areas, with lower population density, result in fewer interactions and slower disease spread.
- Aligned with prior studies that controlled the environment size to simulate population density.
- **Parameter Swept:** Size and grid width of the model to represent urban vs. rural density, while keeping all other parameters constant.

Observations:

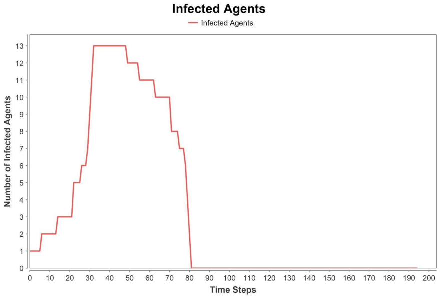
- The Urban environment has higher total infected agent count
- Rural environment has lower total infected agent count

Conclusion:

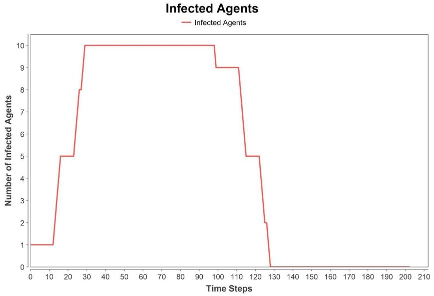
- Since all other parameters remain constant, the difference in outcomes can be attributed solely to changes in population density.
- Changing the environment from urban to rural significantly lowers the total number of infections.

Test 3: Concrete hypothesis: **Increasing infection duration raises the total number of infections over time**

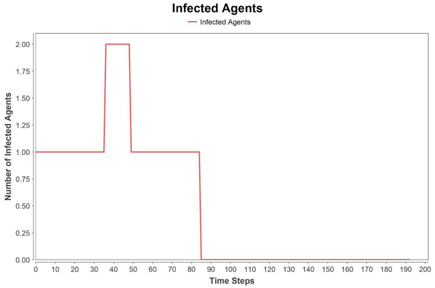
Graph 1: 50 Infection duration in an urban environment



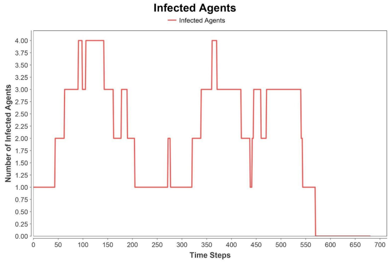
Graph 2: 100 Infection duration in an urban environment



Graph 3: 50 Infection duration in an rural environment



Graph 4: 100 Infection duration in an rural environment



Explanation:

- Prolonged infection duration increases the contagious period, allowing more opportunities for transmission.
- This aligns with prior studies that examined the effects of infection duration on disease spread.
- **Parameter Swept:** Infection duration parameter to analyze its impact on total infections.

Conclusion:

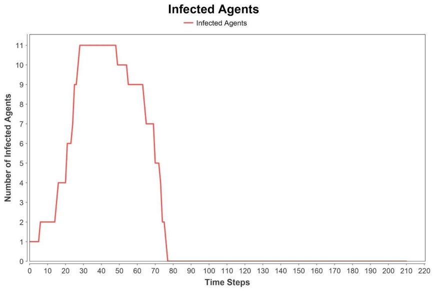
- Infection duration raises the total number of infections in rural areas but does not have a significant effect in urban areas.

Observations:

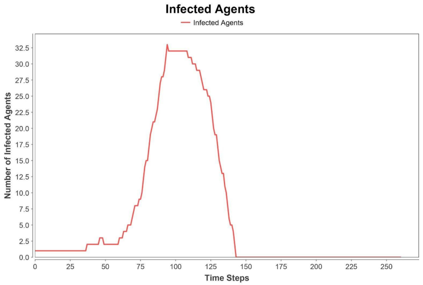
- **Urban environment:**
- Infection duration change leads to similar total number of infections over time in urban areas.
- **Rural environment:**
- Infection duration causes a noticeable difference: infections spike and then drop back to 4, indicating a greater impact in rural settings.

Test 4: Concrete hypothesis: Decreasing the number of infections needed to trigger vaccinations, will decrease the number of infected agents over time.

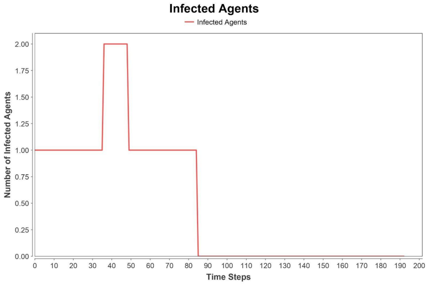
Graph 1: 10 infected agents needed for vaccination, in an urban environment



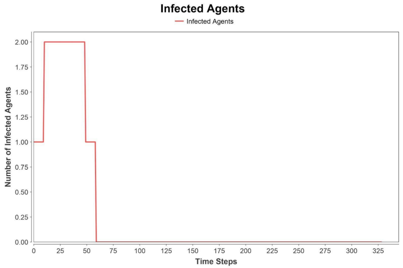
Graph 2: 30 infected agents needed for vaccination, in an urban environment



Graph 3:10 infected agents needed for vaccination, in a rural environment



Graph 4: 30 infected agents needed for vaccination, in a rural environment



Explanation:

- Early vaccination reduces the susceptible population, interrupting the transmission chain earlier and controlling outbreaks more effectively.
- Supported by previous studies highlighting the effectiveness of proactive vaccination campaigns.
- **Parameter Swept:** Number of infected agents required to trigger vaccination, simulating different vaccination strategies.

Conclusion:

- In urban environments, reducing the number of infected agents needed for vaccination effectively decreases total infections.
- For rural environments, the data does not show a significant difference based on vaccination timing.

Observations:

- **Urban graphs:**
- The second graph shows a significantly higher total number of infections compared to the first, indicating the effectiveness of earlier vaccination.
- **Rural graphs:**
- Minimal difference in total infections between the two graphs, suggesting vaccination timing has less impact in rural settings.

To conclude:

Key Takeaway from the Model:

- Vaccination plays a critical role in controlling the spread of infectious diseases, particularly in urban environments where population density amplifies transmission.
- However, the model reveals that proactive vaccination strategies may have limited impact in rural areas, highlighting the importance of tailoring intervention strategies to specific population dynamics.

Implications:

- For rural areas, additional measures like improving healthcare accessibility or targeting high-risk groups earlier in the outbreak
- This shows the need for context-specific public health strategies to effectively mitigate disease outbreaks.

AI transparency statement: Generative AI was not used draft or assist in the making of this project

References

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