A Hybrid Epidemic Spread Model with Congestion-Based Transport

The aim of this project is to model the spread of disease in an urban area in a computationally efficient way. Mathematical models like SIR are analytically tractable and offer closed form solutions, however their underlying assumptions, namely of population averages, are violated particularly at the initial stages of infection when individual variability is critical. Agent-based models on the other hand can be prohibitively computationally demanding, especially as they mimic highly complex interactions. Previous work has investigated the use of agent-based transport models involving each individual agent selecting a list of plans from memory based on econometric scoring. The resulting model is extremely intricate but computationally exhaustive and is only run on 10% of the town population [1]. Other work has proposed a hybrid model, involving agent-based simulation for the early stages of disease propagation, and mathematical modelling for later stages when the proportion of infected individuals is sufficient to support population averages. [2]

The present work attempts to combine these two approaches, implementing an agent-based "congestion" transport model, wherein individuals choose a daily route based on pre-assigned destinations and a memory of congestion, to model individual interactions for early stages of infection, and a compartmental equation-based model to describe the system in later development. The results are compared to previous work to gauge the accuracy of the underlying models. It's hoped that this will yield a model for efficient computation of epidemic spread with a high degree of tunability.

Equation-Based Epidemic Model

The SIR compartmental model is implemented to capture the infection process for individual agents. The model distinguishes between three classes of agent: Susceptible (S), Infected (I) and Removed (R). The time-evolution of the populations of each class are related using a set of coupled differential equations and interaction parameters.

$$\begin{aligned} \partial I &= \alpha S I \\ \partial R &= \beta I \end{aligned}$$

In this model, Removed agents are considered immune.

Agent-Based Epidemic Model

Agent-based models are useful in describing disease transmission involving human behavior and local interaction. The joint behavior of the agents can be very complex and tracking the behavior requires a disciplined approach.

Reproducing real-world migration patterns is done using the congestion model in [3]. A GIS enabled road network representing Aberdeen city is imported to the model and interactions are captured through a proximity-based probabilistic effect. At each iteration, agents within a certain distance of one another will have a probability of disease transmission if one of them is infected and the other is susceptible. The model is implemented in NetLogo and accounts for shared workspaces and shared housing.

Threshold Switch

To determine the switching mechanism between equation-based and agent-based models, a switching threshold is implemented. When the number of Infected individuals in the agent-based model becomes larger than the threshold, the regime is switched to equation-based. To avoid artefacts from the equation-based model, if the population dips below the threshold during evaluation, the regime is switched back to agent-based, with infected agents selected randomly.

To tune the threshold, results of the hybrid model are compared to the agent-based model. In this way, the agent-based model is treated as the “gold-standard” since it captures the intricacies of human and social interaction. It’s hoped that the hybrid model will produce similar results to a purely agent-based model with less computational work.

Model Parameters and Assumptions

The tunable parameters for this model are the total population of agents, the initial distribution of Infected and Susceptible agents, the switching threshold for the hybrid model and the function determining contamination probability as a function of distance. Each commuter is assigned a home and a work address using Ordnance Survey address data (Ordnance Survey 2015). The model accounts for cycling, walking and driving, with a different probability of infection for each. Driving and cycling are assumed to be risk-free, while walking carries a small probability of infection. The greatest probability is assigned to workplaces and shared living spaces. To assess the model, the proportions of Susceptible, Infected and Removed agents as a fraction of the total population are measured.

Sadly, the model omits public transport, which could pose a large risk. However, the city of Aberdeen has a lower usage of public transport than comparable cities and does not have an underground system.

In Literature

Reference [1] attempts to create a highly complex agent-based transport model involving each individual agent selecting a list of plans from memory based on econometric scoring, and local infection interactions. The model is highly intricate and potentially extremely precise, however the computational demands of such a complex algorithm mean that its applicability is reduced. In ref. [1], the model is run on only 10% of the total population.

To try and correct for this, a hybrid model is implemented as described in [2]. Passing from an agent-based regime to an equation-based epidemic model when a threshold is reached allows for significantly faster computational time, and, ideally, little loss in accuracy.

Rather than implementing a complex econometric preference-based model for social transport as in [1], we adapt the congestion based model in [3] to capture individual agents' daily routes. As in [3], we use the city of Aberdeen for the model, and consider three types of transport: walking, cycling and driving. In addition, the same preference model for each travel type is used, using empirical data to model the probability of each choice as a function of commuting distance.

It's hoped that the resulting hybrid model will show similar behaviour to the model in [1], and to a pure agent-based model implemented in NetLogo, with reduced computational work.

References

[1] Hackl, Jürgen and Thibaut Dubernet. "Epidemic Spreading in Urban Areas Using Agent-Based Transportation Models." Future Internet 11 (2019): 92.

[2] Bobashev, Georgiy V., D. Michael Goedecke, Feng Yu and Joshua M. Epstein. "A Hybrid Epidemic Model: Combining The Advantages Of Agent-Based And Equation-Based Approaches." 2007 Winter Simulation Conference (2007): 1532-1537.

[3] Ge, Jiaqi, Polhill, Gary (2018, April 17). "Transport simulation in a real road network" (Version 1.1.0). CoMSES Computational Model Library. Retrieved from: https://www.comses.net/codebases/8a87dbd3-315a-4234-a585-13aedb2f80f3/releases/1.1.0/