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Modelling epidemic spreading in urban areas with large-scale agent-based transport simulations

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1 Introduction

Epidemic spreading is strongly correlated with human mobility. Thus, understanding and modelling human mobility patterns is an important component for the development of realistic epidemic spread models. Nowadays, mobility and traffic have reached a complexity and volume of an unprecedented degree. Millions of people travel billions of miles on international flights each week, while hundreds of millions of people commute on a complex web of highways and railroads most of which operate at their maximum capacity. Despite this increasing connectivity and the ability to visit almost every place on this planet in a matter of days, the magnitude and intensity of modern human traffic have made human society more susceptible to threats intimately connected to human travel. Long range human mobility is now responsible for the rapid geographical spread of emergent infectious diseases [1]. In recent years this has been made evident by several epidemic outbreaks, including the severe acute respiratory syndrome (SARS) in 2003, the 2009 H1N1 influenza pandemic, the Ebola virus in 2013 and the Zika virus epidemic in 2016. In all those cases, the disease started locally but spread rapidly around the globe. Consequently, intense research effort has been devoted during the recent decade to the development of quantitative models for epidemic spreading. Hence, numerous epidemic models have been devised in the past with a wide range of complexity levels. One less complex model is the "classic" approach to model the population and disease spread via a dynamical system, where the dynamics of the infected population is described with a system of coupled non-linear differential equations [2, 3]. With the increasing availability of computer resources, agent-based simulation has become a practical method to study epidemics [4]. Agent-based models are stochastic, spatially explicit, discrete-time, simulation models where the agents represent single individuals which interacting in time and space according to prescribed rules [5]. Such an approach enables to model the entire population in a plausible manner, providing a model of community that acts as if it inhabits the city or the whole country [6, 7]. In this work, disease propagation models to simulate epidemic outbreaks are implemented in a large-scale agent-based transport simulation (MATSim [8]). Based on the agents' movements and activities a spatial-temporal social network is derived. This complex network is used to study seasonal influenza outbreaks in the metropolitan area of Zurich, Switzerland. The results of the model are compared with the "classical" SIR model.

2 Method

Reproducing real-world behaviour of individuals' daily path in an urban setting is done with the open source agent-based transport simulation called MATSim, which uses an iterative approach for agent-based dynamic traffic assignments. Individuals choose activities in different locations. Sequences of activities are generated and equilibrated in MATSim based on a co-evolutionary algorithm, which alters the agent's behaviour from iteration to iteration, trying to find optimal routes, modes and departure times and therefore maximize the total utility of their daily activity schedule [9]. Based on this model, individuals can be identified, who share the same location at the same time and thus have a chance to infect each other. This information is extracted to a spatial-temporal social network where the epidemic spread model is applied.

In order to get a valid result, the epidemic spread model is calibrated based on real-world observations of seasonal influenza occurred in Switzerland in the period 2016/2017 [10]. The dataset contains diagnosed influenza cases by practitioners on a weekly basis. The model results are fitted to the data set using least squares estimation. For implementation purposes, a simulation of a seasonal influenza outbreak in a human population located within the metropolitan area of Zurich, Switzerland (see Fig. 1), is used to implement and illustrate the methodological framework.

Simulation of an influenza epidemic spread in a geographic area is computationally intensive and requires the use of georeferenced data sets and a limited number of individuals interacting in the urban space. Due to computational reasons, the entire population of the area cannot be taken into consideration. For illustration purpose only 1% of the population is used, i.e. one agent represents 100 individuals. In total 15'286 agents, a considered to be involved in an influenza epidemic at an urban scale. Since no behavioural changes of the agents are considered, the results of a single day traffic simulation are reused, only updating the stages (susceptible, infected, recovered) of the agents.

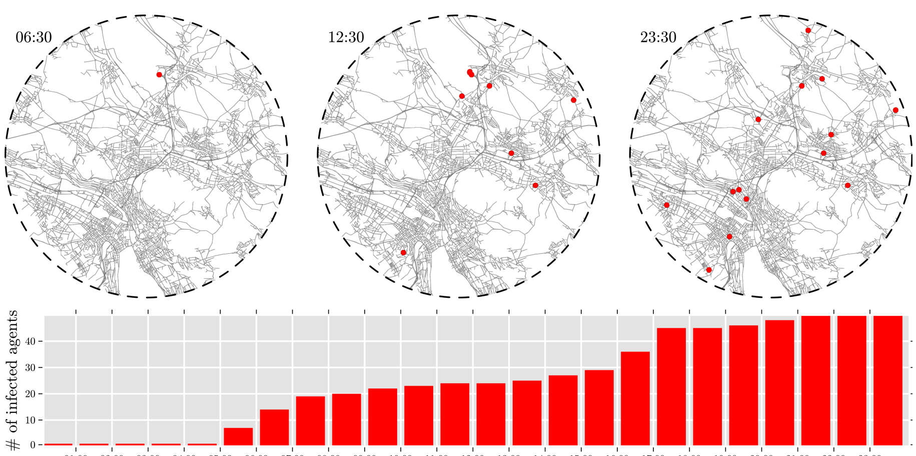

Fig. 1. Temporal-spatial epidemic spreadin the metropolitan area of Zurich.

3 Results

Fig. 1 illustrate the temporal-spatial spread of the virus over one day. Initially, only the most influential agent is infected. At 6:30 he arrives at work where the virus spread to another agent at the facility. Around 12:30 some agents leave the workplace for lunch or end their shift and carries the virus to further. Finally, when the agents come home they also infect their families. At the end of the day, one 50 agents are infected. Fig. 1 (bottom) summarize the number of infected agents over the first day.

Fig. 2 shows the agent-based epidemic spread model and the "classical" compartment SIR model fitted to real data of seasonal influenza in the season 2016/2017 observed in the Zurich area. The best fitted agent-based model from the 21'600 simulations has a least square error of $7.96 \cdot 10^{-6}$ while the SIR model has $3.42 \cdot 10^{-6}$. The SIR model approximates the data with a smooth function, caused by the underlying analytical form, while the agent-based model allows reproducing the non-smooth behaviour.

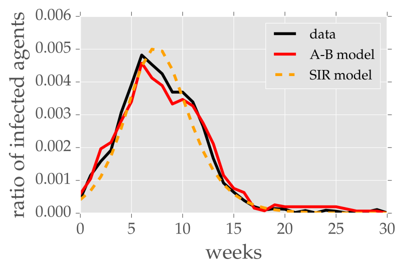

Fig.2. Comparison of SIR and AB model with observed data.

Summary. This study proposes to link epidemiological modelling and transport modelling in a synergistic way to simulates the outbreak of a communicable disease, such as seasonal influenza, in an urban area where different activities take place during a daily citizens' routine. The results of disease propagation simulation indicate that the model is successfully able to generate various scenarios of an outbreak in complex and realistic urban settings by incorporating movement in the agent entities. The addition of mobility allows realistic emulation of daily behaviours of individuals of a population that interact among themselves and that perform stationary activities in fixed spatially located areas after moving from one place to another.

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