Computers, Environment and Urban Systems 51 (2015) 97–105

Contents lists available at ScienceDirect

Computers, Environment and Urban Systems

journal homepage: www.elsevier.com/locate/compenvurbsys

Simulating city-level airborne infectious diseases

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ARTICLE INFO

Article history:
Received 18 October 2013
Received in revised form 11 December 2014
Accepted 12 December 2014
Available online 13 January 2015

Keywords:
Geographical Information System (GIS)
Multi-Agent Systems (MAS)
Infectious diseases
Epidemics

ABSTRACT

With the exponential growth in the world population and the constant increase in human mobility, the possible impact of outbreaks of epidemics on cities is increasing, especially in high-density urban areas such as public transportation and transfer points. The volume and proximity of people in these areas can lead to an observed dramatic increase in the transmission of airborne viruses and related pathogens. Due to the critical role these areas play in transmission, it is vital that we have a comprehensive understanding of the 'transmission highways' in these areas to predict or prevent the spreading of infectious diseases in general. The principled approach of this paper is to combine and utilize as much information as possible from relevant sources and to integrate these data in a simulated environment that allows for scenario testing and decision support. In this paper, we describe a novel approach to study the spread of airborne diseases in cities by combining traffic information with geo-spatial data, infection dynamics and spreading characteristics. The system is currently being used in an attempt to understand the outbreak of influenza in densely populated cities in China.

1. Introduction

City-level airborne epidemics are constant threats to healthy living. With the fast growth of the world's population and the constant increase in human mobility, the danger of outbreaks of epidemics is rising. For example, the pandemic influenza A (H1N1), also known as Human Swine Influenza/Swine Flu, caused an international outbreak in Mexico in 2009, and it caused a serious epidemic in China. Indeed, China is highly susceptible to pandemic influenza A (H1N1) due to the large population and high residential density. According to the report by the Ministry of Health of China, the provinces in mainland China had reported 19,589 confirmed cases, 14,348 cured cases, 10 severe cases and several deaths up to 30th September 2009 (Ministry of Health of China, 2009).

In urban areas with high density such as public transportation and transfer points, where people frequently experience close proximity to one another, we observe a striking increase in the transmission of airborne viruses and related pathogens. To correctly model and simulate airborne epidemics, it is critical that the city infrastructure, which causes these hot spots of transmission, be analyzed and captured in detail. We utilized Geographic Information Systems (GIS) to model the infrastructure of a city that is likely to be threatened by epidemic attacks. GIS facilitates storing, querying and visualizing city infrastructure including roads, regions with diverse functionality, public transportation, and other attributes. To model airborne disease spread, it is important to understand how city infrastructure is used by the inhabitants and acts as the container of infection. We addressed path routing based on city transportation to capture mobility of people and transmissions that occur in localities, especially public transit. This approach was used because in many developing countries such as China, the overly crowded public transportation system can greatly exacerbate airborne epidemics.

Based on geo-spatial information, it is essential to model a local population that dwells in a city with their spatio-temporal behavior. "There is growing recognition that the solutions to the most vexing public health problems are likely to be those that embrace the behavioral and social sciences as key players" (Mabry, Olster, Morgan, & Abrams, 2008). "Human behavior plays an important role in the spread of infectious diseases, and understanding the influence of behavior on the spread of diseases can be key to improving control efforts" (Funk, Salathé, & Jansen, 2010). Obtaining a strong understanding of the 'transmission highways' in urban areas regarding the transmission locations and relevant behavior of people is vital to predict and prevent the spread of infectious

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http://dx.doi.org/10.1016/j.compenvurbsys.2014.12.002
0198-9715/

diseases. Therefore, investigating the patterns that are relevant to social contacts, and consequent airborne virus transmissions, is of great importance.

Although the work on social networks and their application in epidemiological research plays an important role, it is almost impossible to directly correlate the transmission between two agents (represented as vertexes or nodes) that occur along network edges (links) to people's spatio-temporal behavior. This difficulty is because social networks are substantial abstractions of realistic human social contacts, in which spatial information is retracted and replaced by topological information. The reader is referred to literature (Schneeberger et al., 2004; Sloot, Ivanov, Boukhanovsky, Van De Vijver, & Boucher, 2008; Karlsson, Jansson, Normark, & Nilsson, 2008; Mei, Vijver, Xuan, Zhu, & Sloot, 2010b; Mao & Bian, 2010; Mei, Quax, Vijver, Zhu, & Sloot, 2011) for details.

Existing studies, including EpiSimS (Epidemic Simulation System) (Eubank et al., 2004; Barrett, Eubank, & Smith, 2005; Valle et al., 2006; Valle, Hyman, Hethcote, & Eubank, 2007) which is an extraordinary example, grounded this study. EpiSimS is a discrete-event-driven stochastic simulation model used for investigating the spread of diseases in large urban populations. "The original EpiSimS model was based on the city of Portland, Oregon, in which the simulated movement of more than 1.6 million individuals was constructed. Each individual in the simulation was instantiated according to actual demographic distributions drawn from census data, so that the synthetic population had the correct demographics, e.g. age distribution, household statistics, population density, etc." (Valle et al., 2007) However, EpiSimS does not subtly address how people travel, encounter one another and therefore spread airborne diseases at various spots. This concern is a main focus of this study.

We introduced a novel approach in this paper to study the spread of airborne disease in urban areas by combining traffic information with geo-spatial data, infection dynamics and spread characteristics. We combined and utilized as much information as possible from relevant sources and integrated these data in a simulation environment that allows for scenario testing and decision support.

The remainder of this paper is organized as follows. Section 2 addresses the modeling of a city and the synthesis of the population to support the simulations of airborne disease spread. Section 3 presents the GIS-based implementation and visualization of the simulation environment and performs a tentative experimentation. Last, the paper is summarized, and future directions are outlined.

2. Model

2.1. City modeling

We discuss city modeling from the aspects of city partitions and traffic (road and public transportation) networks.

2.1.1. Regions and sublocations

To construct a synthetic city, we break down major metropolitan areas into regions and sublocations (SLs) that reside inside each region. Regions, or land uses in some studies, are pieces of city land serving various purposes, such as agriculture, commerce, medication and education. Sublocations, affiliated with a specific region, represent a realistic-room-like space where people conduct their daily activities and have social contacts. The types of regions and sublocations considered in this study are subject to whether infections frequently occur inside particular spaces.

Each region is categorized into types of agriculture, residence, hospital, school, university and recreation, according to the main facilities that it provides to people, which is consistent with existing work (Valle et al., 2006; Valle et al., 2007; Yang, Atkinson, & Ettema, 2008b; Zhang et al., 2012). In this study, we exclusively considered 7 types of regions – housing (HR), office (OR), school (SR), university (UR), medical (MR), recreational (RR) and transportation (TR) according to the general function assignment of city regions. This region partitioning requires GIS files to comprise clearly partitioned land pieces, and these pieces can be mapped to the aforementioned 7 region types, ignoring those regions (e.g., agricultural regions) that contribute less to the spread of diseases. For instance, industrial regions are mapped to ORs. Transportation regions, as special cases, are assumed to consist of only mobile rooms (i.e., compartments of trains, metros and buses).

The union of all regions is not necessarily equal to the entire city area. In other words, 'holes' are allowed on the city map. Whether regions completely encompass the city depends on the completeness of the fundamental data partition in GIS files, which have little impact on epidemic simulations. For example, agricultural regions can be ignored, due to the infection-hampering factors of low density of population and outdoor air conditions. Moreover, only human–human specific transmission is considered in this study, whereas animal–human transmission is excluded.

A region contains a set of sublocations of different classes. For example, a university region (UR) contains office sublocations (offices), residential sublocations (student dormitories and faculty members' homes), classroom sublocations (classrooms, labs and library space), recreation sublocations (cafeteria, clubs, shops, refectories and restaurants) and possibly hospital sublocations. Specifically, the recreational class includes shops, restaurants, cinemas, supermarkets and all other relevant places that provide services for recreation, relaxation or sales of life necessities. In this study, we classified sublocations as housing (HS), office (OS), classroom (CS), patient room (PS), recreational (RS) and transportation (TS). Table 1 lists the classifications of regions and secondary sublocations in detail.

Sublocations are virtually created with 2 dimensions inside each region. Because sublocations are usually beyond the resolution of GIS files, we generated sublocations and assigned the length and width to each of them in meters. During the course of simulations, individuals are attached to one sublocation at a time and conduct activities (working, staying at home, entertaining, etc.) inside. Accordingly, people interact with only those who stay inside the same sublocation, although visually sublocations can overlap. Additionally, each sublocation is characterized as being either indoor or outdoor, conveying different transmission probabilities of viruses inside the space. For many airborne viruses, outdoor conditions such as sunshine, heat, wind blowing and air circulation can lower the infection probability between the infected and the susceptible.

2.1.2. The road and public transportation networks

City traffic routes are modeled as a road network (RN) and a public transportation network (PTN).

The assemblage of roads in a city can be mapped to a road network (RN). Roads, as the transport infrastructure of a city, are composed of road sections and crossings. We establish the road network, denoting crossings by nodes and sections by edges, as shown in Fig. 1. Edges can be unidirectional or bidirectional, indicating that they correspond to one-way or two-way road sections, respectively. A crossing joins several road sections together. The number of sections (usually 2, 3 or 4) that a crossing links indicates the connectivity of the crossing. Accordingly, the entire city roadway can be mapped to a complex network[1] of vast nodes and edges.

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[1] In the context of network theory, "a complex network is a network with non-trivial topological features that mostly do not occur in simple networks such as lattices" (Newman, 2003).