Modeling short-term epidemics and intervention strategies in cities

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Abstract: Individual-based model (IBM) for simulation of urban influenza epidemic is constructed. In comparison with the past similar models the proposed model has new features: 1)it bases on a real demographical and social infrastructure statistical data; 2)its contacts network is built up with the help of daily routines of different age and social groups of residents. Test simulations were carried out with the use of demographical data on the population of Dresden (Germany). The results obtained showed that the proposed model can be used for the simulation of different epidemics and intervention strategies to contain epidemic or to weaken its consequences.

Keywords: Individual-based models; Influenza epidemic; Intervention measures; Vaccination; Immunity

1. INTRODUCTION

Traditional mean field approach based on a well-mixed paradigm gives birth to models described by the ordinary (or partial) differential equations [Diekmann and Heesterbeek, 2000]. Though such models can sometimes prove useful for understanding main processes they may not take into consideration a complex contact network in a city. For example, it is well known that transmission of many infectious diseases takes place mainly through close contacts (in kindergartens, schools, households, and workplaces) and to a lesser extent through casual contacts (in cafes, cinemas, public transport, etc.). Individual-based models (IBMs) may take into account these (and many other) details [Grimm and Railsback, 2005]. An idea of stable social groups of the population was used by Halloran et al. [2002], Eubank et al. [2004], Kretzchmar et al. [2004], Longini et al. [2004, 2005], and Ferguson et al. [2005] for modeling the capability of containing a possible smallpox and avian flu pandemic in some region or in a whole country with the help of vaccination and antiviral agents. In this paper we propose the IBM that can be used for studying the spread of infectious disease in a city. The model is based on the real distributions of the city's residents over gender, age, social groups, families and number of children in these families, "workplaces" (kindergartens, schools and proper workplaces) and on daily routines of different age and social groups of residents. The main goal of this paper is to give a description of the model and to demonstrate its robustness and capabilities.

2. MODEL DESCRIPTION

IBMs contain usually much more parameters in comparison with the mean field models and any description of such a model has to be well structured. In this paper we use a interesting scheme of the IBM description proposed in the book of Grimm and Railsback [2005].

2.1 Structure

The following objects are included into the model. 1)Object '*Residents*' defined by variables: index, sex, age, age or social group, marital status, workplace index, current location, counter of infection time, counter of infectious time, counter of sick time, counter of immunity time, sign of diagnosis and some others. Population distributions over age, sex, group and marital status are prescribed in accordance with a city's demographic statistics.

2)Object ‘*Families*’ defined by variables: index, family’s size and family’s members. Families are organized taking account the household statistics.

3)Objects ‘*Kindergartens*’, ‘*Schools*’, ‘*Workplaces*’ defined by variables: index, capacity, registered number of residents, real number of residents, real number of infectious persons.

4)Object ‘*Entertainments*’ defined by variables: index, number of residents, number of infectious persons. Number and capacity of objects ‘*Kindergartens*’, ‘*Schools*’, ‘*Workplaces*’, ‘*Entertainments*’ may be in principle prescribed in accordance with statistical data if they are available.

5)Object ‘*Disease*’ defined by variables: duration of latent period, duration of non-infectious period, duration of sickness, duration of the immunity obtained after recovery, transmission probability due to contacts in kindergartens, transmission probability due to contacts in schools, transmission probability due to contacts in workplaces, daily transmission probability due to contacts in families, transmission probability due to contacts in public places, transmission probability due to contacts in public transport, probability to get the correct diagnosis from doctor, probability to get sick after the latent period, probability to get immunity after recovery, probability to die during sickness, probability to go to workplace after being diagnosed, probability of hospitalization right after being diagnosed.

For our main goal of testing and validation of the model it is sufficient to assume that natural history parameters of the disease are constants.

2.2 **Processes**

Changes in demographic structure of population during the short-term epidemic are small and can be neglected. It means that there are no births, marriages, divorces and changes of "workplaces" and all deaths are only due to the disease concerned. External actions which are specified by the variables of the object ‘*Disease*’ and by initial data are mainly the intervention measures such as vaccination, isolation, temporary closing schools and kindergartens, etc. The basic process in our model is that of the infection spreading by contact network. Such contacts are treated on the basis of a daily schedule for residents. This daily routine for week-days is the following:

1) All residents, except sick ones (that is residents, who were diagnosed), nursing mothers, employed mothers staying with sick children, housewives and pensioners, go to their "workplaces". At each "workplace" the number of incoming "workers" is counted as well as the number of infectious persons among them. These two numbers are used for calculation of probability for a healthy person to have a contact with infectious one. The product of the probability to have contact in the “workplace” and the probability to become infected through direct contact gives the full probability to become infected at “workplace”. Because of high contact intensity inside kindergarten groups and school classes the probability of contact with infectious individual therein is assumed to be equal to 1.

2) Mothers staying with sick children, healthy housewives and pensioners may visit some public places, such as shops, medical centers, museums and etc. Probability to become infected in such public places is calculated in the same way as in “workplaces”.

3) After a working day the possibility to become infected is checked for all healthy residents, and in case, if the infection has occurred, the variable "counter of infection time" is set at 1.

4) There is some probability to visit entertainment, leisure or other public places in the evening for families without sick members, as well as for single adults (healthy or with indeterminate diagnosis) and "adult" children from families with sick members.

5) After coming back home the possibility to become infected is checked again for each healthy person, who was absent from home, and in any case, where the infection has occurred, his or her variable "counter of infection time" is set at 1.

6) There is a finite probability of being infected in a public transport. This possibility is checked during each way to "workplaces" or public places.

7) Then at the end of each day the possibility to become infected is checked for each healthy member of families which have at least one sick member. In the course of the latest check-up the variables of each resident characterizing his or her state with respect to the disease are analyzed and updated if it is necessary.

8) At the rest days residents have not to go to "workplaces" but they still may go to other public places.

2.3 **Concept**

The appearance of a certain number of virus carriers which can infect other residents is a starting point of an epidemic. Simulation of disease spread begins from its start and lasts till its attenuation. Simulation time step is one day. All variables with a dimension of time are measured in days. The daily routine described above defines the dynamics of number of the healthy, infected, infectious, sick and immunized people. During a simulation run the following parameters can be calculated:

1) Number of residents (total and daily), who were infected in different places (at "workplaces", in public transport, at home, and in public places).

2) Number of healthy, infected and immunized residents (total and daily) in different age groups.

It is impossible to get reliable real data for the former group. Data for the latter group being known for the past epidemics might be used to calculate the transmission probabilities through contacts and to test, verify and correct the model itself. Unfortunately in literature there is (to the authors' knowledge) scant information on the topic.

2.4 Initialization

Initialization is the most complicated and time-consuming procedure in our model due to the necessity of multiple searches among residents for appropriate persons in order to construct the families of given size and structure in accordance with the household and family statistics. Besides that, the level of complexity is determined by the amount of available statistical data used in the model.

2.5 Initial data

Demographical, social and normative parts of the initial data were those that proved available for Dresden (Germany). The choice of disease transmission probabilities in different age and social groups will be commented in the next section. We suppose that influenza is the infectious disease of interest (values and ranges of values used in simulation runs are given in parenthesis):

Number of residents ($N = 300000$)
Male percentage (48%)
Male distribution over age
Female distribution over age
Family size distribution (families without children 10%, 1 child 45%, 2 - 25%, 3 - 15%, 4 - 5%)
Nursery and preschool age (1 to 5 years old)
School age (over 6 years old)
School graduates age (18 years old)
Legal age of maturity (18 years old)
Age of child whose mother may get a leave certificate in case of his or her illness (under 14 years old)
Age of unmarried dependent child living with family (under 21 years old)
Pension age for men (65 years)
Pension age for women (65 years)
Maximum fertile age for women (under 40 years)
The largest difference in ages between spouses (15 years)
Percentage of preschool children who attend nursery, kindergarten or preschool (80%)
Percentage of initially infected people (N_{inf} = 0:1, 0.5 and 1%)
Probability of disease transmission in kindergartens (0.25)
Probability of disease transmission in schools (0.3)
Probability of disease transmission in workplaces (0.15)
Probability of daily disease transmission in family ($p_h = 0.03 - 0.07$)
Coefficient in probability of disease transmission in public transport (0.015)
Probability of disease transmission in public places (0.15)
Latent period (3 days)
Non-infectious latent period (1 day)
Illness period ($d = 6$ or 7 days)
Length of immunity after recovery (200 days)
Probability to visit doctor during latent period (0.0)
Probability to visit doctor after latent period (1.0)
Probability to get a reliable diagnosis from doctor ($p_d = 0.7 - 1.0$)
Probability to go to work after being diagnosed ($p_w = 0.0 - 0.2$)
Probability to become ill after latent period (1.0)
Probability to get immunity after recovery (1.0)
Probability to die from disease (0.0)
Probability to visit public places at weekdays (0.2)
Probability to visit public places at weekends (0.4)
Probability to visit public places for pensioners (0.5)
Capacity of kindergarten group (15)
Capacity of school class (22)
Capacity of workplace (20)
Capacity of public place (40)

Since the main goal of this work was the model's testing we assumed that there is no "unemployment" in any age groups. Given the capacities of corresponding "workplaces" and public places this assumption allows to calculate the required number of such places.

3. RESULTS AND DISCUSSION

A real distribution of men in Dresden (Germany) over age (solid line) and the model distribution used for simulations in this work (dots) are shown at Figure 1. One can see that the model distributions are in good agreement with the statistical data. Of course, the similar results take place for the distribution of women over age too. Therefore various means of the model distributions have to be in good agreement with the corresponding ones of the real distributions. Figure 2 shows fractions of men and women over age and social groups.

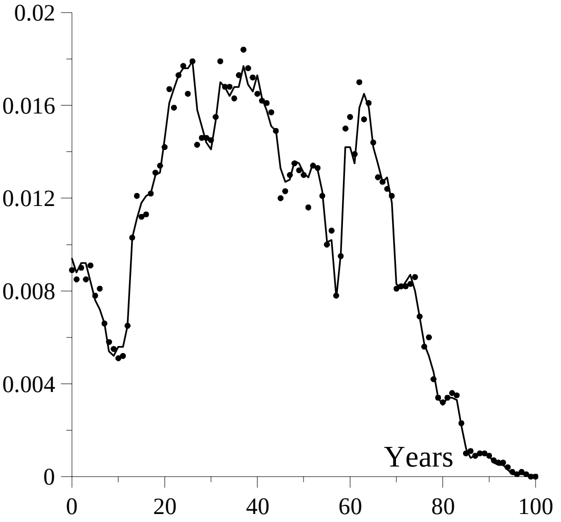

Figure 1. Distribution of men over age (line - statistical data, dots - model distribution).

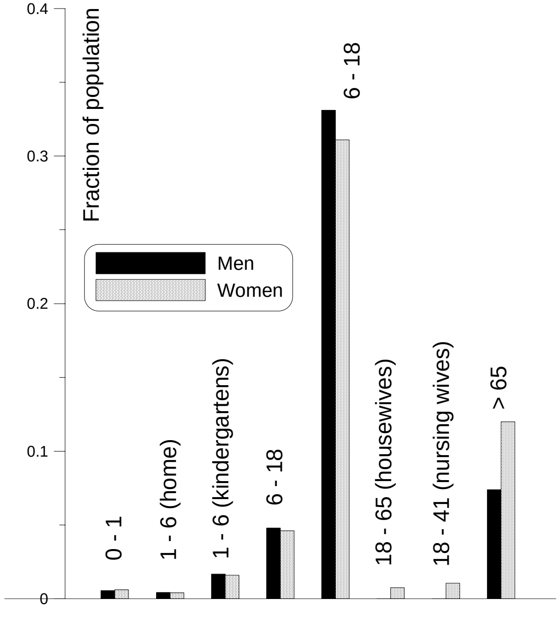

Figure 2. Fractions of age groups

Let us consider as a basic variant the simulation run in which $N_{inf} = 0{:}1\%$, $p_h = 0{:}05$, d = 7, $p_d = 0{:}8$, $p_w = 0{:}0$ and values of the other parameters are equal to those presented in the Sect. 2.5. The values of the probabilities of the infection transmission through the contacts in different age and social groups were evaluated from the given infection attack rates for a usual seasonal influenza epidemic: 11% (< 1 yr old), 55% (ages 1-5 yrs), 83% (ages 6-18 yrs), 12% (ages 18-65 yrs), and 10% (> 65 yrs) residents; overall infection attack rate was equal to 21.3%. The fractions of infected residents and the overall infection attack rate for basic variant are shown at Figure 3 as functions of time. The duration of the model epidemic is about of 2 months and its overall infection attack rate is about 21%. IBMs help us to study the epidemic spreading "on the inside", i.e. to get detailed information about the processes. Figures 4 and 5 illustrate a change of the fractions of residents infected in different places and those of infected in different age groups over time. Numerous simulation

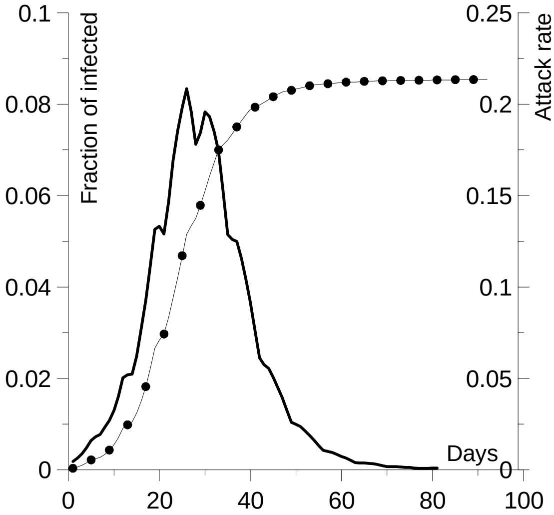

Figure 3. Fraction of infected residents and overall attack rate as functions of time.

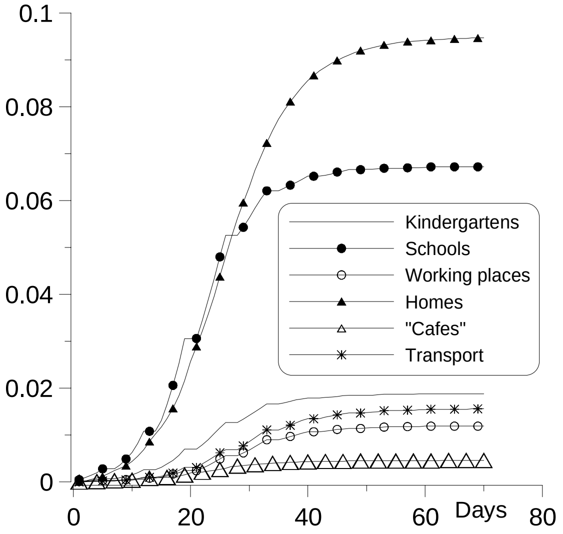

Figure 4. Fractions of residents infected in different places

runs were carried out and the results obtained allow us to make the following conclusions:

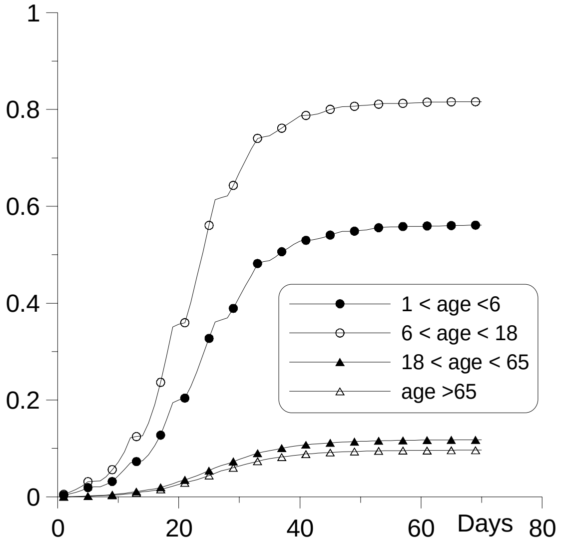

Figure 5. Attack rates in different age groups

1. School and pre-school children are the main groups taking part in the disease spreading. It can be explained by the age peculiarities of their immune system and by the duration and intensity of their contacts. From the point of view of overall infection attack rate these groups are the top-priority candidates for vaccination. The simulation runs for vaccination level of 0, 10, 20 and 30% of school children confirm this well known conclusion (Figure 6). For the simplicity it was assumed that the mortality during or after the disease is zero and the vaccination guarantees protection against the disease.

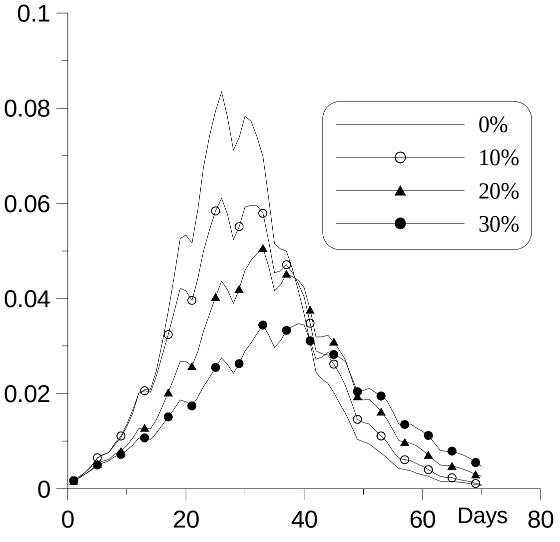

Figure 6. Fractions of infected residents for different percent of school children vaccination.

2. Since entertainment places, households and public transport comprise a mix of people of different age and social groups, their influence on the disease spreading in a city may be appreciable. The basic variant results show that the contacts in households are the most effective (Figure 4). Qualitatively this result is not unexpected since the contacts of healthy members in a family with sick person can be quite close and prolonged. For the basic variant the full probability of transmission in family during the sickness of a family member is approximately equal to 0.4. A decrease of this probability (for example as a result of a better isolation of sick persons, as recommended by doctors) would decrease the overall infection attack rate. The fractions of infected residents and the overall infection attack rate for the smaller value of this probability are shown at Figure 7. Indeed the isolation extent strongly influences the overall infection attack rate.

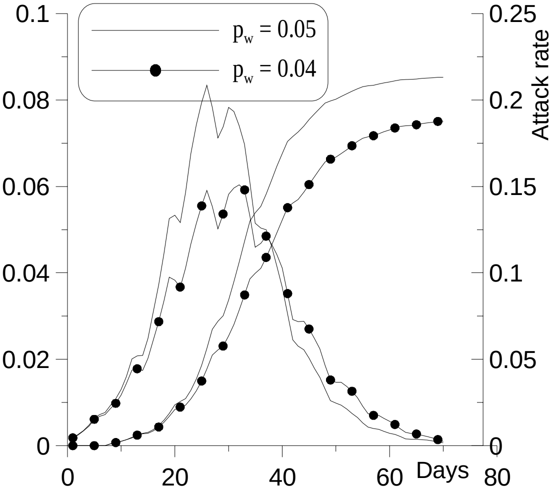

Figure 7. Fractions of infected residents and overall attack rates for different transmission probabilities at home

3. It is clear that the epidemic dynamics should be sensitive to the disease duration. The simulation results for the disease duration shortened by one day (for example, due to a treatment by a new medicine) confirm this statement: the peak value of infected residents and the overall infection attack rate decrease considerably (Figure 8).

4. Local governments in many cities declare extra vacations in kindergartens and schools during the flu epidemic supposing that it can decrease the overall infection attack rate. Figure 9 shows the results of the epidemic simulation for a week-long extra vacation declared at different stages of the epidemic.

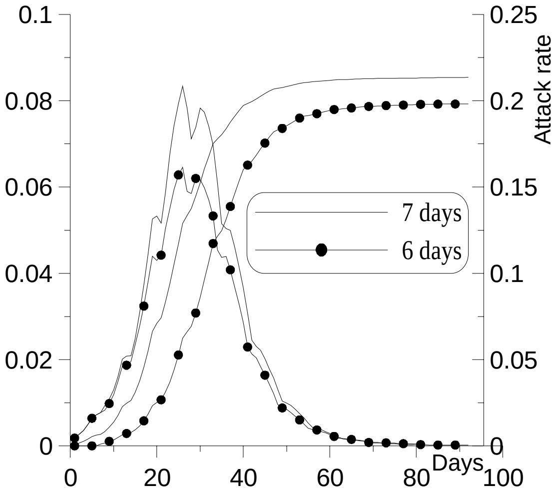

Figure 8. Fractions of infected residents and overall attack rates for different durations of the illness

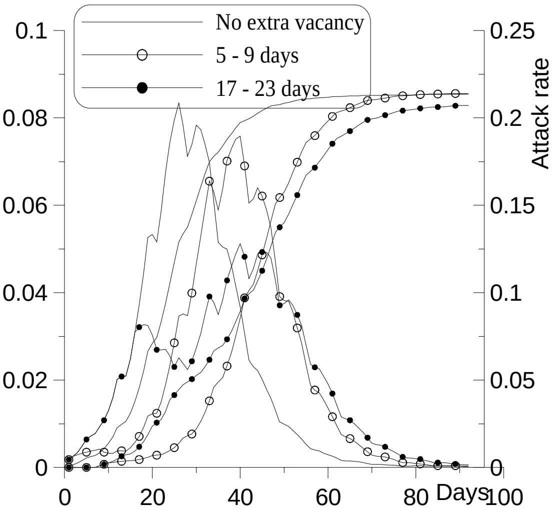

Figure 9. Fractions of infected residents and overall attack rates for different extra vacancies

One can see that the extra vacation does not practically change the overall infection attack rate but increases the epidemic duration. So if the vacation is declared at a proper time it may considerably decrease the peak load on the city's health care institutions.

4. CONCLUSIONS

The results described above show that our main goal has been achieved: the proposed individual-based model can be used for comparative study of the efficiency of different intervention measures before and during epidemics. However, before such a study the model has to be expanded by an inclusion in it a lot of other important factors (for example, daily immigration of workers from suburbs, groups of high risk and medical care workers and etc.).

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