CONCEPTUAL DESIGN OF AN ACTIVITY-BASED SPATIO-TEMPORAL DATA MODEL FOR EPIDEMICS TRANSMISSION ANALYSIS

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ABSTRACT:

Recently GIS have been used in the surveillance and monitoring of diseases and control of epidemics. Most of those mapping systems use aggregated datasets. This aggregated datasets are not sufficient to support the analysis of epidemiological transmission if the disease is spread mostly person by person from region to region such as SARS - Severe acute respiratory syndrome. This paper develops a mobility-oriented spatio-temporal data model to support SARS transmission analysis in a GIS environment by identifying spatial and temporal opportunities for activity participation. The model can support the tracing and predication of spatially varying, temporally dynamic and individually based epidemiological phenomena. A prototype system based on the data model is implemented by a case study based in Hong Kong.

1. INTRODUCTION

Due to its spatial analysis and display capability, GIS is well suited for studying association between location, environment and disease. Recently GIS have been used in the surveillance and monitoring of diseases and control of epidemics. Severe acute respiratory syndrome (SARS) is a highly infectious and potentially lethal atypical form of pneumonia that begins with deceiving common flu-like symptoms. All around the world during the peak of the outbreak in the first half of 2003, SARS was negatively affecting every aspect of daily life: economic, social, travel, work, at school and home. Many universities and research institutes, and some GIS companies provided internet SARS mapping services, which allowed public health decision makers, travelers and local populations at risk to visually monitor and appreciate at a glance changes, trends and patterns buried in different online SARS datasets that were continuously varying with time during 2003 outbreak (Boulos, 2004).

However, most of those mapping systems use aggregated datasets. This aggregated datasets are not sufficient to support the analysis of SARS transmission since the disease is spread mostly person by person from region to region following the network of contact between them. Through this network, SARS disease spread through space and time, just like the most infectious diseases. Since the contact between persons is realized through the common activities of them, this paper develops an activity-based spatio-temporal data model to represent such spatially varying, temporally dynamic, and individually based epidemiological phenomena.

We will first review the transmission process of epidemic disease in order to understand the relationship between individuals and the relationship between individuals and the environment. It will set forth the requirement of the spatio-temporal data model. Then we will present the design of the data model based upon mobility-oriented view by incorporating the transmission process. Finally, a prototype system will be implemented by a case study based in Hong Kong.

2. CONCEPTUAL FRAMEWORK OF EPIDEMIC DISEASE TRANSMISSION

The individual-based epidemiological modeling requires the data model to consider discrete individuals as the modeling unit. The model should also represent the characteristics and behaviors of the individuals, the relationship between them and environment, and how these characteristics and interactions change through time and space (Bian, 2004).

(1) individuals are unique

Individual-based requires that a conceptual model be based on the following assumptions: (1) individuals are different; (2) individuals interact with each other locally; (3) individuals are mobile; (4) the environment for individuals is heterogeneous.

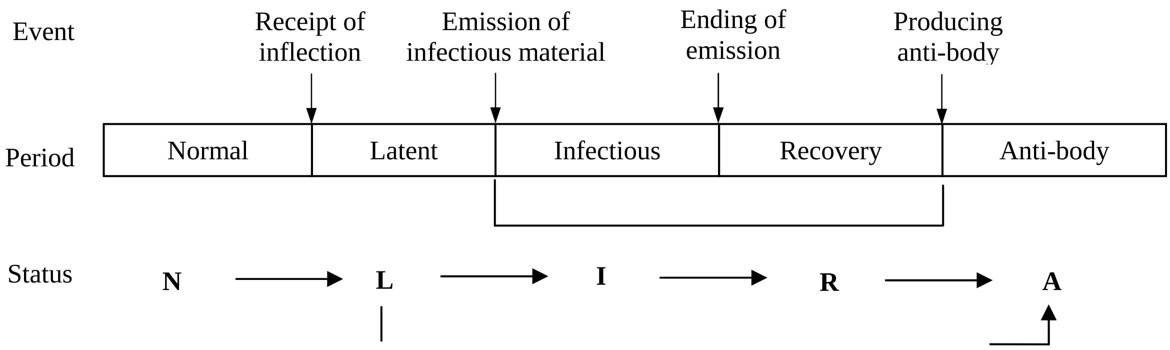


Figure 1: An individual infection process and status

These considerations are widely supported in several disciplines that have experienced a major shift away from population-based and towards individual-based approaches (Adams et al., 1998; Bian, 2000; Bousquet et al., 2001).

(2) disease develops as discrete events

An infection history can be considered as a sequence of distinct period, each of which begins and ends with a discrete event. The critical periods include the latent, the infectious, and the incubation periods. The critical events include the receipt of infection, the emission of infectious material, and the appearance of symptoms (Baily, 1975).

(3) Interaction/contact between individuals

An individual participates in a sequence of activities on a daily basis. Some of the activities are stationary and some are mobile. Stationary activities occur at a physically fixed location, such as a home or a workplace. At these locations, the individual may interact with other individuals in a group activity. When a group dissolves, an individual travels through space and time to another location, often joining another group. Local infections occur at a stationary location and the long-distance dispersions occur through travel (Miller, 2004).

(4) Infectious factors

The probability of infection depends on the attributes of the individual, such as age, the infection status of other individuals in the group, and the contact structure within the group (Cliff, et al, 1990).

3. AN ACTIVITY–BASED SPATIO-TEMPORAL DATA MODEL

The conceptual framework of epidemic disease sets forth the guidelines for our design of the database.

(1) an individual infection process -- statuses of individuals

Since infection history is a sequence of distinct period, it is appropriate to represent the individual infection as a series of discrete events and periods (see Figure 1). The discrete periods indicate the infection status of an individual and are part of the individual's characteristics.

There are five statuses of an individual, corresponding to five periods, triggered by four events:

- Normal (or health): the individual is normal and is not infected;
- Latent: the individual receives the infection, but does not emit infectious material;
- Infectious: the individual is in the period of emitting infectious material;
- Recovery: the symptom appears and the individual stays in the hospital or isolated till recovers;
- Carrying anti-body: the patient recovers and produces anti-body to the infection;

These five statuses are represented as N, L, I, R and A in Figure 1, respectively. When an individual is in the infectious period, if he contacts with others, others might be infected.

(2) mobility of individuals

The activities of a person can be considered as the interaction of a person with locations, either *Stay_at* or *Travel_between* locations. If we use mobility to represent the characteristics of travel-between, and no-mobility to describe the characteristics of stays-at, this view can be considered as a mobility-oriented view. This view treats activities as dynamic and occurring within the largely static transportation space. It deals explicitly with the moving behavior of discrete objects (individuals) (Wang & Cheng, 2001).

Under the element of *Stay_at*, the location and duration (which is defined by the starting time and the end time) of the stay is indicated. The element of *Travel_between* is entailed by from where to where the travel takes place, how long the travel lasts (which is defined by the start and end time of the travel), what transport mode is used, and which path it traverses. All *Stay_at* and *Travel_between* are connected by topological relations between time and locations.

(3) Formalize infection transmission -- constraints for interaction

The infection transmits through the direct contact of individuals. The interaction of individuals is realized through common activities, either "Stay_At" a same location at a same time, or "Travel_Between" locations by a same travel model at a same time. When a person Pj who is in a normal status ("N"), interacts with a person Pi who is in infectious status ("I"), the infection will be transmitted form Pi to Pj. This process of transmission can be formalized as:

If Status(Pi)= "I" and Status(Pj)= "N" (1)

and $Activitities\ (Pi) \cap Activities(Pj) \neq \Phi$ (2)

then Transmit(Pi,Pj)

Equation 1 represents the constraint for individuals' status and Equation 2 represents the spatio-temporal constraint of the interaction.

Equation 2 can be further divided into two cases. Case one refers to the situation that two individuals are in a stationary mode, i.e. stay at a same location. Case two refers to the situation that two individual are in moving mode, i.e. travel together between locations.

For the case of a stationary model, i.e., Stay_At, the constraint $Activities\ (Pi) \cap A(Pj) \neq \Phi$ requires that

$L_1 = L_2$ and
$Ts_i \leq Te_j \leq Te_i \leq Te_j$ or
$Ts_j \leq Ts_i \leq Te_j \leq Te_i$ or
$Ts_i \leq Ts_j \leq Te_j \leq Te_i$ or
$Ts_j \leq Ts_i \leq Te_i \leq Te_j$.

(3)

The contact time of the two individuals for these four situations are as follows, respectively

$$\text{Contact\_time(i,j)=} \begin{cases} Te_i - Te_j \\ Te_j - Ts_i \\ Te_j - Ts_j \\ Te_i - Ts_i \end{cases} . \quad (4)$$

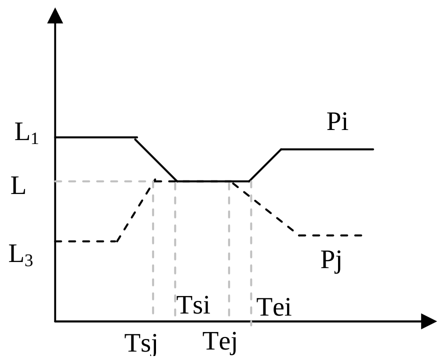
For the case of moving mode, i.e., Travel_Between, $Activitities\ (Pi) \cap A(Pj) \neq \Phi$ requires that

$Ls_i = Ls_j$ and
$Le_i = Le_j$ and
$Ts_i = Ts_j$ and
$Te_i = Te_j$. (5)

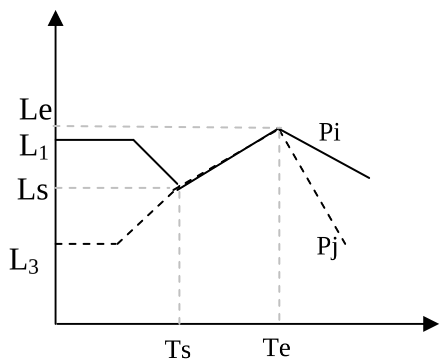
The contact time of the two individuals for this case is

Contact_time(i,j) = $Te - Ts$ (6)

These two cases are illustrated in Figure 2, with Figure 2a representing one situation of "Stay_At" and Figure 2b representing the situation of "Travel_Between".



(a) Stay together



(b) Travel together

Figure 2: Two cases of interaction of two persons

(4) Incorporating infectious magnitude

Taking the infectious magnitude into account, extract information should be provided for the description of the physical environment and personal status.

For the properties of Household, the population density (Pdensity) of the area where the household locates should be considered as the indicator of the infectious magnitude. Higher the density of population is, stronger the infectious magnitude is.

For the properties of Person, the age can be considered as an indication of being infected. For different age, the ratio of being infected is different. Therefore, the date of birth should be provided in order to derive the information of age.

In the properties of Location, different lavational type (Ltype) corresponds to different infectious magnitude. So does the activity type (Atype) of Activity, travel model (Tmode) of Travel_between and stay type (Stype) of Stay_At.

Therefore, following objects are essential for the database, which are defined by the properties in the brackets. The infection magnitude related properties are in italic.

HOUSEHOLD(Hid, Pnum, Income, Home Address, *Population density*);

PERSON(Pid, Name, Salary, Role, Working place, Occupation, *Date of birth*, *Infectious Status*);

LOCATION(Location address, *Location type*, Opening time, Closing time, Facility)

ACTIVITY(Aid, *Activity type*, Earliest starting time, Latest starting time, Duration)

TRAVEL-BETWEEN(Location1, Location2, Stating time, Ending time, *Travel mode*)

STAY_AT(Location, Starting time, Ending time, S*tay type*)

(5) Infectious principle
Here environmental factor refers to the *Population density*, *Activity type*, *Stay type*, *Location type*, or *Travel mode*.

The infectious probability of an individual can be calculated by the following formulas as

Infectious probability = f(age, environmental factor, contact time) (7)

4. CASE STUDY

We used the case presented in (Wang & Cheng, 2001) to test our model. Table 1 presents the information of six families. The information about the husband and wife of these six families are presented in Table 2. The husbands' and wives' daily activities are collected as listed in Tables 3 and 4.

In order to incorporate infectious factors into the transmission process, the following tables are defined. Table 5 represents the activity/location/stay type with the infectious magnitude. Table 6 presents the relationship of travel model with the infectious magnitude, Table 7 presents the age with the infectious magnitude and Table 8 presents the population density with the infectious magnitude.

Here we try to simulate the transformation of the disease within these six families. To begin, one infected individual is introduced into the population. In case Person 2 (Nancy) is infected. The infection for the rest of the population depends on three operational steps. The first is to identify the individuals who contact with this infected individual based upon their activities (presented by the Tables of Stay_At and Travel_Between). In the second step, those individuals are assigned an infected status according to infection probability calculated based upon Equation (7). The third step identifies those already infected individuals who will contact other individuals and continuous the spread of infection throughout the population. To simplify the calculation, the simulation uses the infection probabilities listed in the above tables (Tables 5-8) for the susceptible and a one-day latent period and a four-day infection period for the infection.

Table 9 presents the transformation of the disease within these six families for 14 days (here only the activities of "Stay_At" is used in the case stay since the programming for the activity of "Travel_Between" is still under development). It shows that in Day 1 Person 2 is infected and is infectious. Person 2 transferred the disease to Persons 1 and 3 in Day 2 so that they were in Latent period. In Day 3, Person 1 transferred the disease to Person 5, and Person 3 transferred the disease to Person 4. So Persons 4 and 5 were in Latent period in Day 4. In Day 5, Person 2 showed the symptom of the disease and was transferred to hospital in recovery period. Persons 1, 3, 4 and 5 were in infectious period in this day. So does Day 6. In Day 7, Persons 1, 2 and 3 were in recovery period and Persons 4 and 5 are infectious. So does Day 6. In Day 9, Persons 4 and 5 joined others to be in recovery period. The transformation stopped in Day 9.

Based upon Table 9, we can identify the status of individuals so that the total number of infectious individuals can be summarized. We can also trace the transmission from person to person, and trace the transmission from place to place based upon the locations associated with the activities of these persons. In case isolation policy should be implemented to stop the spread of the disease, we can locate the individuals to be potentially infected, due to their contact with the infectious individuals.

5. CONCLUSIONS

This activity-based model conceptualizes the spatial and temporal interaction of travel and activity behaviors using the concept of mobility. The activity patterns are conceptualized as a sequence of staying at or traveling between activity locations. Based upon the mobility-oriented view, the transmission of epidemic disease is modeled as spreading through the common activities involved by two or more persons, either staying in a same place or traveling by a same transportation means. The model can support the predication and tracing of epidemics spread by identifying spatial and temporal opportunities for activity participation, which will facilitate the epidemiological studies and policy making to control epidemics.

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Table 1: Information of families.

HID	PERSON_NUM	INCOME	AddressID	Pop_Density
1	3	70000	Parkview Garden	3
2	4	70000	Xiao Shun Chun	3
3	2	60000	Ma An Shan	3
4	4	120000	Royal Ascot	4
5	4	80000	University	2
6	4	100000	Mei Lin Chun	4

Table 2: Table of PERSON of six families.

PID	Name	HID	ROLE	OCCPUATION	Working_Address	Date_Of_Birth
1	Winter	1	Husband	Teacher	Baptist University	19660701
2	Nancy	1	Wife	Researcher	University	19690808
3	Jone	2	Husband	Teacher	University	19600305
4	Krystal	2	Wife	Sectary	University	19610506
5	Samen	3	Husband	Teacher	Baptist University	19550403
6	Ingeberg	3	Wife	Housewife	At-home	19600908
7	Mike	4	Husband	Teacher	Baptist University	19480101
8	Linda	4	Wife	Housewife	At-home	19500705
9	Lincon	5	Husband	Teacher	University	19780604
10	Karain	5	Wife	Student	University	19800912
11	Peter	6	Husband	Teacher	Baptist University	19640321
12	Amy	6	Wife	Business	Central	19651126

Table 3. Part of table of *STAY_AT*. (Wang & Cheng, 2001)

SAnum	Pid	Laddress	Stype	Ts	Te
1	1	Parkview Garden	4	7:00:00 AM	8:00:00 AM
2	1	Kowloon Tong	1	8:30:00 AM	12:00:00 PM
3	1	Kowloon Tong	3	12:00:00 PM	1:00:00 PM
4	1	Kowloon Tong	1	1:00:00 PM	7:00:00 PM
5	1	Parkview Garden	4	8:00:00 PM	11:59:00 PM
6	1	Festival Walk	2	7:10:00 PM	7:50:00 PM
7	2	University	1	9:00:00 AM	12:00:00 PM
8	2	University	5	12:00:00 PM	12:30:00 PM
9	2	Parkview Garden	4	7:00:00 AM	8:30:00 AM
10	2	University	1	12:30:00 PM	5:30:00 PM

Table 4. Part of table of *TRAVEL_BETWEEN* (Wang & Cheng, 2001)

TBnum	Pid	Laddress1	Laddress2	Ts	Te	Tmode	BSAnu	ASAnu
1	1	Parkview Garden	Kowloon Tang	8:00:00 AM	8:30:00 AM	1	1	2
2	2	Parkview Garden	University	8:30:00 AM	9:00:00 AM	1	9	7
3	1	Kowloon Tang	Festival Walk	7:00:00 PM	7:10:00 PM	4	4	6
4	1	Festival Walk	Parkview Garden	7:50:00 PM	8:00:00 PM	1	6	5
5	2	University	Parkview Garden	5:30:00 PM	6:00:00 PM	1	10	11
6	3	Xiaochui Chun	University	8:40:00 AM	9:00:00 AM	3	12	19
7	4	Xiaochui Chun	Kowloon Tang	8:00:00 AM	8:30:00 AM	1	18	
8	4	Kowloon Tang	University	8:30:00 AM	9:00:00 AM	1		13
…	…	…	…	…	…	…	…	…

Table 5. Table of *Activity/Location types/ Stay type*

Atypeid	**Type**	**Infectious Magnitude**
1	Working Place	5
2	Shopping Center	4
3	Sporting Center	3
4	Home	5
5	Railway Station	4
6	Restaurant	3
7	Theatre	3
8	School	5

Table 6. Table of *Travel_ Mode*.

TMode	**TRAVEL MODE**	**Infectious Magnitude**
1	Train	3
2	Bus	4
3	Car	5
4	Walking	1
5	Bike	1
6	Airplane	4

Table 7. Table of Age with infectious magnitude.

AgeClass	**Age**	**Infectious Magnitude**
1	0-2	5
2	3-12	4
3	12-30	2
4	30-40	1
5	40-60	3
6	>60	5

Table 8. Table of Population density with infectious magnitude.

DClass	**Density (per km^2)**	**Infectious Magnitude**
1	0-100	1
2	101-1000	2
3	1001-10000	3
4	10001-10,000	4
5	10,000 – 30,000	5

Table 9: Transmission of Disease from person to person

	Day 1	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**	**Day 8**	**Day 9**
Infectious	2	2	2 1 3	2 1 3	1 3 4 5	1 3 4 5	4 5	4 5	
Latent		1 3		4 5					
Recovery					2	2	1 2 3	1 2 3	1 2 3 4 5