

## A SPATIO-TEMPORAL POPULATION MODEL FOR ALARMING, SITUATIONAL PICTURE AND WARNING SYSTEM

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### ABSTRACT:

Natural and man-made hazards, disasters, and concerns such as the increasing amount of terrorism, cause insecurity for people and society. Therefore, crisis management with respect to urban structure becomes one of the core tasks of governments. Population information is essential during the rescue planning process. Population density can be estimated by using various statistical methods. Often it is impossible to estimate the size of the population of a certain area. Most population distribution models do not take into consideration the temporal variation in population location; this causes poor estimation results. In this paper, we present a spatio-temporal population model, which is used for calculating the number of people in a certain area at a certain time. The model combine object-oriented spatio-temporal model with users' knowledge. Population size is estimated on the basis of built-up environments in the real world. Built-up environments such as buildings and roads are divided into different categories; each category is one *spatio-temporal object*. The model produces reasonably accurate results since each spatio-temporal object is modelled separately according to its own characteristics. The model is also flexible, as most of the estimation methods are based on user knowledge. The model is simulated using Java programming language. As a result, the model produces a text file, which can easily be adapted to most information systems.

### 1. INTRODUCTION

This research work is part of the "Alarm, Situational Picture and Warning System for Chemical, Biological, Radiological, and Nuclear (CBRN) and the Natural Disaster Incidents" (UHHA) project (Molarius et al., 2009). Several other organisations, such as Valtion Teknillinen Tutkimuskeskus (VTT), the Finnish Meteorological Institute (FMI), Insta Ltd, Helsinki University and Finnish Chemicals Ltd., are involved in this UHHA project, the goal of which is to set up an alarm, warning, and information exchange system that rescue personnel can use in the event of an emergency. A chemical accident in Kuusankoski city is selected as a study case for this research project. Finnish Chemicals Ltd. is a company that produces hazardous chemicals. It is located in Kuusankoski in the south-eastern part of Finland. To cope with an event such as a chemical leakage accident, a dispersion model has been created by FMI. This dispersion model can define the risk area based on an evaluation of the releases, source terms, and atmospheric dispersion of hazardous chemicals (Finnish Meteorological Institute). This risk area is the location input to the spatio-temporal population model. The spatio-temporal population model is used to estimate the exact number of people inside the risk area at a specific time. The UHHA server is the main UHHA user interface and was implemented by VTT (Molarius et al., 2009). It is a web user interface that requests population information from the population model and sends the population model results to the interorganisational Crisis Manager System (iCM) (Insta Oy, 1997). The Insta iCM System is designed to support decision making and the coordination of operations between crisis management organisations, both in international and domestic crisis

situations (Insta Oy, 1997). Figure 1 shows the whole system architecture of the UHHA project.

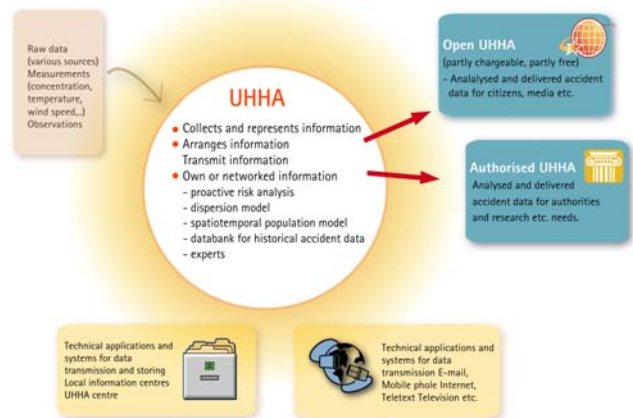


Figure 1. UHHA project architecture (Molarius et al., 2009).

Ahola combined Yuan's three-domain model (Yuan, 1996) and Langran and Chrisman's (Langran, 1992) space-time composite model to create a spatio-temporal population model to support risk assessment and damage analysis (Ahola, 2007). The accuracy of the model is low since it estimates people's location based on their occupation information. Time is stored as an attribute in the database, which causes a lack of flexibility. The data from SeutuCD are used as the main location and attributes input dataset, which only exists in Helsinki Metropolitan Area. All these drawbacks indicate that we need a spatio-temporal

population model that can be applied to any municipality of Finland and that will produce results that are more accurate.

In addition to Ahola's idea, The population density maps, which represent the average population density for a statistical unit, for instance city or country, can be considered the simplest models of population density distribution (Sweitzer and Langaas, 1994). Longley has introduced a population density estimation method by using kernel functions (Longley, 2005). Liu introduced a regression and area to point residual kriging method to improve the population density interpolation accuracy (Liu et al., 2008).

The main emphasis of this paper is on developing a spatio-temporal population model, prototyping it by using programming language and examining how the model can be used in the application in question. The population model has been designed to be generic, so it could be used not only in the city in question but also in any Finnish municipality for crisis management.

## 2. BACKGROUND AND THEORY

### 2.1 Spatio-temporal models

A model is an approximation and simplification of reality. Several spatio-temporal modelling methods have been developed during the past 10 to 15 years. El-Geresy identified conceptual modelling of spatio-temporal domains and classified them into several categories: location-based models, time-based models, event-based models, object- or feature-based models, process-oriented models and causal models (El-Geresy, 2002). In a location-based model, the space is divided into locations by means of a grid; for each location, the changes are recorded in a list representing successive changes in the features of that specific location, together with their corresponding time (El-Geresy, 2002). One example of a location-based model is Langran's temporal raster data model (Langran, 1992). Time-based models include Armstrong's *snapshot models* (Armstrong, 1988; Hunter and Williamson, 1990), and *space-time cube models* (Hägerstrand, 1970). Peuquet (Peuquet and Duan, 1995) introduced an event-based model that deals with abstracted relations based on event. An object- or feature-based model is an extension of a vector model; these include Langran's *base state with amendment model* (Langran, 1992), Langran and Chrisman's *space-time composite model* (Langran, 1992), and Worboys' *spatio-temporal object model* (Worboys, 1992). Process-oriented models classify the spatial relations into specific processes (El-Geresy, 2002). *Causal models* specify the temporal relation in terms of cause and effect (El-Geresy, 2002).

In addition to the above-mentioned spatio-temporal models, Yuan presented a three-domain model (Yuan, 1996). In his three-domain model, semantic, temporal, and spatial objects are defined as three separate domains and time is modelled as an independent concept. Geographic concepts and entities are represented by linking these three types of objects from the object perspective or layer dynamically (Yuan, 1996).

### 2.2 Object-oriented spatio-temporal data model

#### 2.2.1 Definition of spatial object

Before talking about object-oriented data modelling, the definition of *object* has to be clear. From the static point of view, an object is a collection of named *attributes*, each of

which takes a value from a specified domain (Worboys, 1994). From the dynamic or behavioural point of view, an object can perform a set of operations under appropriate conditions

(Worboys, 1994). Therefore, Worboys has defined an object as state (static) plus functionality (dynamic) (Worboys, 1994). *Object types* that have similar behaviours form object groups. The objects associated with an object type are called *occurrences* (Worboys et al., 1994). Mattos et al. state that an object must be identifiable, relevant and describable (Mattos et al., 1993).

Spatial dimensions have always played an important role in GIS research. *Spatial object* refers to the object that contains a spatial domain. Spatial object in general can be divided into discrete such like point, lines or field model that represents the spatial phenomena as continuous surface or layer (Zhang and Goodchild, 2002). There are several dimensions in which spatial object attributes may be measured. These include spatial, graphical, temporal and textual/numeric (Worboys, 1994). For instance, a road network is a spatial object as it has its coordinates in the real world (spatial), a line representing its cartographic form at a different level of generalization (graphical), times when it was created in the real world and system (temporal), and attributes describing the length of street address (textual/numeric).

#### 2.2.2 Temporal objects

Traditional Geographic Information System (GIS) applications describe reality in a static manner; the time dimension is not taken into account. In real life, most phenomena change with time and because of this temporal information has played an important role in the GIS modelling process. Time can be divided into two dimensions in information systems (Worboys, 1994). *Database time* refers to the time when transactions take place in information systems, such as the time when data is stored in the database. It is also called *system* or *transaction time*. *Event time* refers to the real-world or valid time when events actually occur in the application domain.

During the spatio-temporal modelling process, spatio-temporal data is the first core element that needs to be considered. Based on the above defined time dimensions and duration of the time, dynamic data can be divided into *real-time data*, *near-real-time data*, and *time-stamped data* (Nadi and Delavar, 2003). *Real-time data* refers to those geospatial data, such as traffic volume, that are collected and imported to GIS as soon as an event occurs. *Near-real-time data* are related to the data that need updating at any given moment and also need visualization and analysis before they can be used in GIS. *Time-stamped data* refers to data that have a time attribute attached to them (Nadi and Delavar, 2003).

#### 2.2.3 Object-oriented spatio-temporal model

In the object-oriented model, the information space is decomposed into objects. Geographical information can be modelled by two classes of model, i.e. the *fielding-based* model and *entity-based* model. In the class of *entity-based* models, the information space is treated as populated by discrete, identifiable entities (or objects) with a geo-reference (Worboys, 1994). The association between entities is called *relationship*. Worboys has extended the original object-oriented model in the temporal dimension and so developed the object-oriented spatio-temporal model (Worboys, 1992). This model represents the world as a set of discrete objects consisting of spatio-

temporal atoms by incorporating a temporal dimension orthogonal into the 2D space (Worboys, 1992). Each spatio-temporal atom contains changes in both space and time, but no changes are recorded between them (Worboys, 1992). The object-oriented spatio-temporal model is suitable for modelling the complex phenomena since it breaks through the limitation of relational form and directly captures the in-depth semantics of the application domain.

### 2.3 Combine object-oriented spatio-temporal modelling with users' knowledge.

Based on Worboys' idea, a spatio-temporal population model can be created by combining object-oriented spatio-temporal model and users' knowledge. Figure 2 illustrates the modelling structure. This model is not concerned with how the spatial object's static attributes change according to the temporal dimension, which means spatial objects that presented in this model are stable (not time dependent), but the knowledge that gain from the entity relationship with the spatial object is time dependent. The temporal attribute is not necessarily stored in the database. For instance, this spatio-temporal population modelling started with an entity-based model. People stay inside spatial objects (residential buildings) at certain times. A relationship is an association between entities, for example "stay inside". In this case, the temporal dimension of spatial object refers to the time when there are people inside. Population size can be gained by using the attribute values of the residential buildings together with this entity relationship and users' knowledge. This knowledge is updated according to time. For instance, the estimated average population size for a residential building during the morning hours was 10 since most people leave to go work or school. At night, most people stay at home, so estimated population size changed to 50. Further detailed population size estimation methods will be introduced in Section 3.2. Smith and Smith have proposed aggregation and generalization abstraction constructs that were used in this model as well (Smith and Smith, 1997). Worboys has extended these abstraction constructs to generalization, specialization, aggregation, association, ordered association and polymorphism (Worboys et al., 1990). Generalization constructs enable groups of entities of similar types to be considered as a single higher-order type (Worboys et al., 1990). For instance, all the major roads, minor roads or walking paths are grouped into one spatio-temporal object called *roads*. For each spatio-temporal object, the population size changes individually according to time.

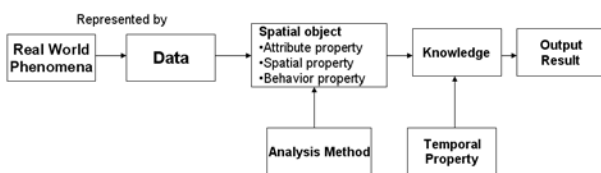


Figure 2. Combine object-oriented spatio-temporal model with users' knowledge .

## 3. MATERIAL AND METHODS

### 3.1 Data processing

The dataset used in spatio-temporal population modelling comprised Finnish Base Register data, National road and street

database (Digiroad), the Topographic Database, and a dispersion model.

In Finland, every municipality is responsible for collecting its regional land information data. The law relating to the Finnish Base Register data is derived from the Population Information Act and the Population Information Decree. One dataset used in this research project is part of the Kuusankoski Base Register data, called the Building Information System. It was in Excel format. This dataset was used to estimate size of population inside buildings in the risk area.

Another dataset comprised Digiroad data, which can be used for modelling road networks. It was in vector format. Digiroad data is a national database that describes the geometry and physical features of roads and streets in Finland. The Finnish Road Administration is responsible for maintaining and updating the data.

The Topographic Database maintained by the National Land Survey was chosen as the background map. In addition, a dispersion model was created by experts from the Finnish Meteorological Institute. It was delivered in a Shape file format.

The Kuusankoski Building Information System and Digiroad data were first converted into Shape files by using ArcMap. A dispersion model was used to represent the risk area and added to the ArcMap as a separate layer. Within the risk area, the Shape file dataset (Kuusankoski Building Information System data and Digiroad data) was first selected and then imported to separate Geodatabase files. Figure 3 illustrate the dataset attributes and data processing.

### 3.2 Methods

Object-oriented spatio-temporal model combine with users' knowledge is chosen for implementing this spatio-temporal population model. For the case of Kuusankoski, eleven spatio-temporal objects, namely roads, office buildings, old people's homes, day care centres, residential buildings, shops, hospitals, hotels, schools, industrial buildings, and restaurants and bars, are defined. For each spatio-temporal object, the population size changes individually according to time.

#### 3.2.1 Modelling roads and residential buildings

The average number of people on the road network inside the risk area was calculated by summing together the "Traffic density" values of different road segments in Road Geodatabase file (see figure 3). Traffic density attribute refers to how many people pass by certain road segment in one minute. A similar method can also be used to estimate population size in residential buildings. The maximum number of people inside the residential buildings was calculated by summing together the "Total amount of inhabitants" values in Buildings Geodatabase (see figure 3). Total amount of inhabitants attribute refers to how many people registered this building as their home address.

#### 3.2.2 Modelling office buildings, old people's homes, day care centres, restaurants and bars

For office buildings, old people's homes, day care centres, and restaurants, it was assumed that the average floor area used by one person is a constant. In Buildings Geodatabase file, there is an attribute value representing the floor area of the building. Therefore, the maximum number of people inside the building

can be estimated on the basis of the total floor area of the building divided by the average floor area that one person uses. The floor area used by one person is estimated on the basis of the user’s knowledge; therefore, this spatio-temporal population is also a knowledge-based model.

$$\text{Population size} = (\text{Total floor area of building}) / (\text{average floor area that one person uses}) \quad (1)$$

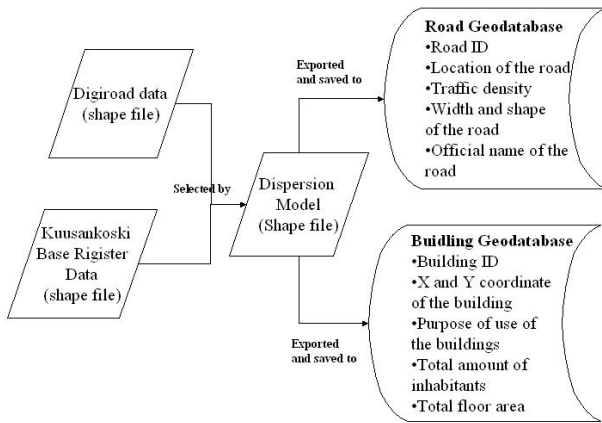


Figure 3. Data processing.

### 3.2.3 Modelling hospitals, schools, hotels, and industrial buildings

For these buildings, the relationship between the population size and the floor area is not linear. In Finland, the number of such buildings is limited due to their purpose or use. The X and Y coordinates of the buildings can be found in Buildings Geodatabase file; ArcGIS address locator can be used to find a building’s address on the background map. After that, an organisation’s name can be defined according to its address. The population size for the organisation can be found through, for example, the organisation’s homepage. This method might be time-consuming, but it works for most Finnish municipalities because there are not an excessive number of hospitals, schools, hotels and industrial buildings inside any particular limited area. Although it is time-consuming, this method can nevertheless give quite accurate estimation results.

### 3.2.4 Modelling shops

In the Building Geodatabase file, the floor area for shops can be found; this varies from 200 square metres to 4000 square metres. Shops can be grouped into four categories according to their floor area. Average number of customers for different shop categories can be estimated based on statistical material or user’s knowledge and saved in Buildings Geodatabase file with attribute name “Customers”. The number of people inside shops in the risk area was calculated by summing the number of “Customers” values together in the Buildings Geodatabase file. Table 1 shows the shop types and their corresponding floor area and number of customers.

Shop type	Floor area ( $m^2$ )	Estimated number of customers
Small food shop	200-500	40
Small supermarket	700-2000	130
Small shopping centre	2000-4000	300
Big shopping centre	4000-	500

Table 1. Estimated number of customers for different types of shops.

### 3.2.5 Modelling the temporal aspect

The temporal aspect is taken into account by assigning weights to the estimated maximum or average number of people inside each spatio-temporal object. The weights vary according to time. Table 2 shows an example of assigning weight to estimate the average number of people using road networks and the maximum number of people inside shops according to time. For instance, on weekdays between 7 and 10 o’clock, the average number of people using selected roads was 500, whereas in reality the number was greater because at that time most people were travelling to work. The weight assigned to this population size was 3, which means the estimate of population size in the road network at this time was approximately 3 times 500, which equals 1500. In Finland, most shops open at 10 o’clock, so the estimated weight of population size in shops on weekdays during the period 7 to 10 o’clock was only 1/10(some shop workers come to work before 10 o’clock).

	Weekday 07.00-10.00	Weekday 10.00-16.00	... Weekday 19.00-22.00
Roads	3	1/2	1/3
Shops	1/10	2/3	2/3
.....			

Table 2 Estimate of the weight of population size using roads and in shops according to time.

Office buildings, day care centres, schools, and industrial buildings have regular opening and closing hours. Estimate of the weight of population size inside these buildings is zero outside the opening hours and one inside the opening hours. Interviews and some other statistical materials are needed to compute people’s daily travelling habits, such as the time that people usually travel to work, back home and have a meal. This information can be used to estimate the weight of the population size inside residential buildings, hotels, old people’s homes, restaurant and bars. For instance, estimate of the weight of population size inside a restaurant is one or at least ½ during the lunch time. It is also possible to get statistical information about the number of visitors during different time periods in big shopping centres in Finland. This information can be used to estimate the weight of population size inside shops. Hospitals have regular opening and closing hours. Therefore, population size decreases outside the opening hours, but not to zero because some patients and staff remain in the hospitals during the closing hours. Estimating the weight of population size for the roads is problematic. The population size on the roads increases during the time when people travel to work and back to home. However, it is difficult to give the exact weight of population size during different time periods on the road network and this should be included in the future development plan.

## 4. RESULTS

This spatio-temporal population model was implemented by using Java programming language on ESRI GIS platform. Figure 4 shows the UML representation of the software architecture. Figure 5 shows the user interface. In the upper part of window, there are lists of all the tools that help the user to interact with the background map. After the user has uploaded the map, different map layers can be turned on or off by clicking the on/off check box. Figure 5 shows the roads,

buildings and buffer-layer check boxes were turned on. The buffer layer was produced by the Finnish Meteorological Institute. It includes four zones, the smallest of which has the highest level of pollution. The legend button is used to show the legend of the selected layer. Time was grouped into 17 categories and listed in a Set Time combo box. The time was specified as hours, so the user can easily choose the time category according to accident time.

Figure 6 shows that a new window, 'Buffer Analysis Results', pops up after the user has clicked the 'Analysis' button. It shows all the spatio-temporal objects defined in Section 3. For each spatio-temporal object, a different estimation method is used for estimating the population size. The user can click the 'Show Result' button to estimate the population size for the corresponding spatio-temporal object. Figure 6 illustrates the simulation of population size estimation methods for office buildings. After the user has clicked on the office building's 'Show Result' button, a dialog box pops up that shows the total floor area of the selected office building was 348 square metres. In the dialog box, the user can set a parameter that is used to define how many square metres one worker uses. In this case it was 23. The result, which was called 'Count People', was calculated by using the total floor area of the selected building divided by the parameter that the user set, which gave the result as 15. After that, a weight 2/3 was given according to time. The final estimation of the population size was 15 times 2/3, i.e. 10. A similar user interface and method was also used for old people's homes, day care centres, restaurants, and bars.

For roads, hospitals, hotels, schools, industrial buildings, restaurants and shops, the estimated population size for the corresponding buildings will appear in the corresponding text field after the user clicks on each 'Show Result' button. The methods introduced in Section 3 were used, so the results came by querying Geodatabase files and summing the corresponding attribute value together. The weight for different spatio-temporal objects was added after the query process.

The 'Total' button was used to sum all the spatio-temporal objects analysis results together. In this case, estimated population size inside the risk area is 3164. The user can use the 'Report' button to create a text file of analysis results. The 'Save' button is used to save the report.

accuracy. As a result, the model will produce a text file, which can easily be adapted to other systems.

### 5. CONCLUSION

The model is flexible, because most of the estimation methods are based on the user's knowledge. The user can update his/her knowledge frequently in order to produce more accurate results. The model also gives reasonably accurate results. Each spatio-temporal object is modelled individually according to the character of the object. Especially in the case of industrial buildings, hospitals, schools, and hotels, the population size information comes from the web pages of the organisation concerned, which have information with a very high level of

One expert is needed to process the data and set up the software environment before the model can be used. He/she should be familiar with the Java programming language and basic GIS tools, such as ArcGIS and ArcEngine API. Some real-world

objects, such as places for hobbies and leisure, fire stations, police stations, sports centres etc., are ignored in this model. The reasons for this are a lack of data and, in some cases, the rather small population size inside these buildings. There are no data available for modelling forests, water regions, and airplanes in this project. This will be added to the future development list and implemented in the next version.

Because of the time limitation, only a text file format result is achieved. With a little more effort, a Shape file could also be produced as an output of the model. Buildings and roads were selected manually by using ArcMap selection with the 'location' tool. In the future, it will also be possible to add a selection function to the model so that the selection can be made automatically after the buffer layer has been turned on.

The uncertainty of the spatio-temporal population model is not discussed in this paper. Uncertainty may be caused by the lack of data of locations, incorrect attribute data and incorrect weight of population size. Model can be calibrated by doing interviews and collecting statistical data about people's daily habits in order to get more correct weighting of population size for each spatio-temporal object. Data quality should also be concerned in the future development work.

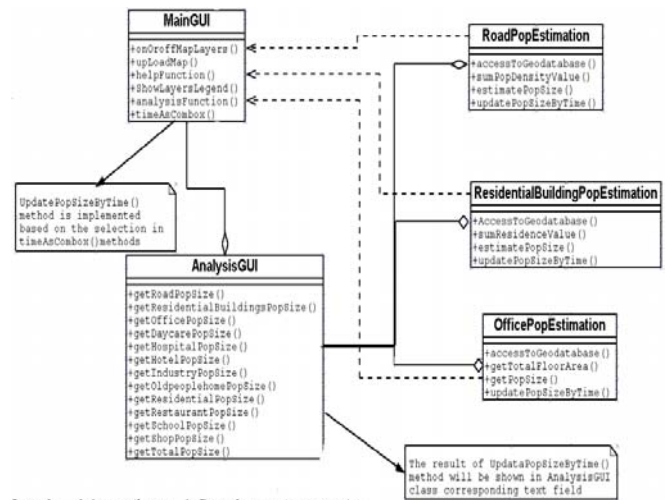


Figure 4. Spatio-temporal population model software UML diagram.

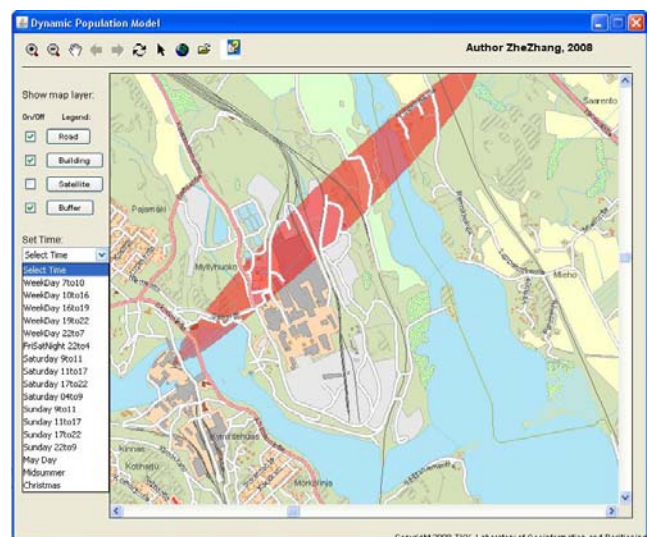


Figure 5. Spatio-temporal population model user interface.



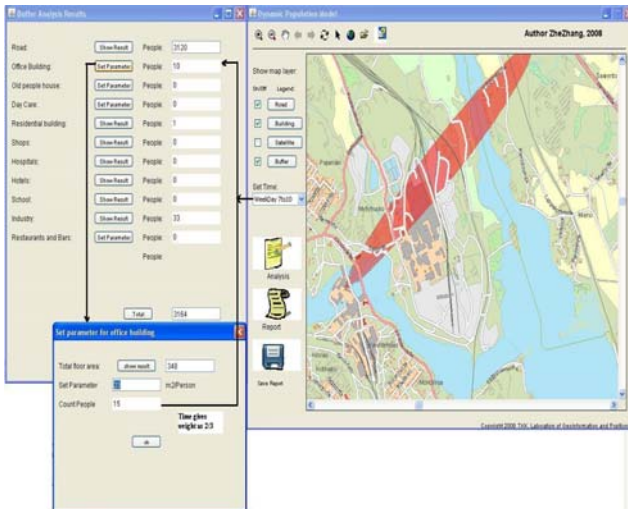


Figure 6. An example of estimating population size in an office building.

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