Submitted for the International Journal of Geographical Information Science

Article type:

A spatio-temporal population model to support risk assessment for emergency response decision-making

TERHI AHOLA*†, KIRSI VIRRANTAUS†, JUKKA MATTHIAS KRISP† and GARY J. HUNTER‡

†Helsinki University of Technology,
Department of Surveying, Cartography, and Geoinformatics
PO Box 1200, FIN-02015 HUT, Finland

‡The University of Melbourne
Department of Geomatics
Parkville, VIC 3010, Australia

The aim of this research is to develop and implement a simple spatio-temporal model of population location and activity that may improve risk assessment for decision-making in both the Finnish Fire and Rescue Services and in the Finnish Defence Forces. The motivation for the research is that present risk models fail to fully take into account the spatial variation in population location during the day or night and at different times of the week. We use spatio-temporal modelling methods to represent the population, in addition to the concept of visual analytics to represent and value the decision outcomes. The study site is located in the centre of Helsinki. The model uses basic population and workplace data from SeutuCD, which is a data collection maintained by the Helsinki Metropolitan Area Council (YTV). By means of this model we intend to advance risk assessment, which considers the consequences of accidents. This model has the potential to help decision-makers to evaluate plans in several application areas, for example more reliable evacuation plans and resource allocation. In addition to the application-related technological research a more generic conceptual framework about decision-making supported by spatio-temporal knowledge and visual analytics is presented. The Finnish Defence Forces funded the research and the work will continue with the support of the Fire and Rescue Services.

Keywords: spatio-temporal population modelling; spatio-temporal knowledge; risk assessment; emergency response; decision-making.

1. Introduction

Spatio-temporal information about the population is important in applications that aim to model any phenomenon that has a relationship to human activity. Modelling the probability of accidents or other unwanted events, as well as their consequences, is one of the most interesting applications and parts of risk assessment for decision-making in the fire and rescue services and related military activities. The main goal of risk analysis

* Corresponding author. Email: terhi.ahola@tkk.fi

is to identify the risks to society posed by both normal and extreme situations and to develop ways to control those risks. Risk analysis is based on risk assessment, and in the case of the above-mentioned applications a spatio-temporal model of population can be important in the identification of high- and low-risk areas at different times of the day and week. Although people are the major causes of incidents (Krisp *et al.*, 2005) the consequences of these incidents that affect people are also amongst the first ones that should be avoided. The spatio-temporal model described in this article was first developed to support a military application for damage analysis of fire attacks (Ahola, 2006). In that application the model was used for estimating the consequences of different bomb attacks on people and the built-up environment. This spatio-temporal model can also support the emergency preparedness planning and resource allocation of the Fire and Rescue Services. Typically, these two actors are involved in joint operations such as major disasters, hazards, terrorist attacks, and other crisis situations. Thus it is natural and necessary to develop common tools for their individual applications.

From the decision-making point of view the focus in our research is in long-term decision-making, not in short-term time-critical decisions. The application software, risk assessment procedure and results considered in this paper are intended to support planning and analysis, rather than emergency response and resource logistics—even though the model could be useful also for emergency response purposes. In this case the decision problems are spatial in nature, such as where are high- and low-risk areas, how many people are there in a particular area at a certain time, or which are the most appropriate places for fire stations. According to Simon (1960) the decision-making process consists of three major phases: intelligence collection, design and choice. Our focus here is on the intelligence gathering phase where raw data are processed into an appropriate form for GIS use to support the decision-making process. We emphasize the importance of recognizing and identifying the various sources and forms of knowledge in the decision-making process. Design of alternatives and making choices are in minor focus in our research.

Recent developments in visual support for analytical reasoning and decision-making are very relevant to the application problem and our results in this paper. In the NVAC research agenda (Thomas *et al.*, 2005) and in the recently published "Exploring Geovisualization" book (Dykes *et al.*, 2005) the importance of applying visualization to spatial decision support is clearly demonstrated. In our research the usefulness of using visualization in intelligence collection is also verified.

Accordingly, the main emphasis of this paper are on developing a spatio-temporal model of population (location/density), applying it to the application software, and investigating how visualisation and visual analytics are used in this process of supporting risk assessment for emergency decision-making. The paper is organised as follows. In sections 2 and 3 we provide a theoretical and conceptual background and framework for the research as well as a review of previous studies undertaken in risk assessment in Finland. In section 4 we present the materials and methods used in the modelling process, while section 5 presents the results of the study. We conclude the paper with a discussion of those results, we make suggestions for future research directions, and summarise the research achievements and findings.

2. Spatio-temporal knowledge and visual analytics supporting decision-making

2.1. Spatial decision support and visual analytics

Spatial decision support system is an interactive, computer-based system designed to support a user or a group of users in achieving a higher effectiveness of decision making while solving a semistructured (not completely programmable) spatial decision problem (Malczewski, 1999). . Spatial decision support systems aim to integrate database management systems with analytical models, graphical display and tabular reporting capabilities and relevantly the expert knowledge of decision makers (Moore, 2000). Malczewski classifies spatial decision support systems according to their ability to manage with semi- or unstructured problems. Completely structured problems can be solved by algorithmic solutions while semi- or unstructured problems require knowledge and ability to support flexible strategies (Malczewski, 1999). Spatial decision-making has been investigated for example in hazardous material route planning (Frank *et al.* 2000, Huang *et al.* 2004) and in many other application areas (Jankowski *et al.* 2001, Andrienko *et al.* 2001). Generally, the models for generating decision alternatives operate in the background behind the interface, detached from decision-makers' insights and qualifications. Each alternative can be evaluated and analysed in relation to others. The alternatives are investigated and the ranking depends upon the decision maker's preferences, with respect to the importance of the evaluation criteria. Clearly, it is critical to incorporate the decision makers preferences into the decision-making process and to provide a model that may reduce the overall amount of data used for the decision, especially in the context of problems involving collaborative decision-making. Malczewski (1999), Jankowski *et al.* (2001) and MacEachren (2001) among others have explored the use and value of geographic information systems in collaborative decision-making.

In turn, visual analytics can be defined as the science of analytical reasoning facilitated by interactive visual interfaces. In a wider sense, people use visual analytics tools and techniques to: (1) derive insight from very large, dynamic, ambiguous and often conflicting data; (2) detect the expected and discover the unexpected; (3) provide timely, defensible and understandable assessments; and (4) communicate assessments effectively for action (Thomas *et al*., 2005). Research in sense-making provides the theoretical basis for understanding what a planner and decision maker does and, according to Thomas *et al*. (2005), many reasoning tasks follow a standard process of:

- Information gathering;
- (Re-) presentation of the information in a form that aids analysis;
- Development of insight through manipulation of this representation; and
- Creation of some knowledge product or direct action based on knowledge insight.

These steps are incorporated into a loop, which shows that the representation and visualization of information is a crucial step in the knowledge creation process. This process might be repeated several times and in turn results in a "sense-making" or "knowledge crystallization task". Within the concept of visual analytics, the sense-making loop is the focus of our study with (re-) presenting the data. Visualization and visual analytics are tools for integrating the user/decision maker into the system. Interaction between the decision support system and the user is the key for both collecting and using the human intelligence, which is required in the system when nonprogrammable, semi- and unstructured problems need to be solved.

2.2. Spatio-temporal modelling

Geographical information consists of three domains: space, theme, and time (Sinton, 1978). Traditional GIS describe reality in a static way in which the time dimension of the information is not taken into account. However, most real-world phenomena are dynamic in nature and the temporal dimension of geographical information has gained a significant amount of attention within the past 10-15 years. This attention has been driven by the need to analyse how spatial phenomena change over time, and by the availability of the data required and increased computer power, which is needed to perform space-time calculations.

The core element in spatio-temporal modelling is concerned with change over time and how to represent it in GIS. Sinton (1978) and Yuan (1996a) have investigated different spatio-temporal change types and how they could be measured, represented, and analysed in GIS. According to Yuan (1996a) there are six major types of spatial and/or temporal changes in geographical information, which are attribute changes, static spatial distribution, static spatial changes, dynamic spatial changes, mutation of a process, and movement of an entity. In this kind of approach when one component (location, theme or time) of the geographical information is measured, a second component is systematically controlled and the third component is fixed.

A suitable data model is another key concept when speaking of spatio-temporal modelling. The data model defines how information is stored in a database and how it is searched. Traditional data models, such as vector and raster models, limit the ways in which dynamic information can be represented. Several pieces of research have developed diverse ways to integrate time in geographical databases. Spatio-temporal data models can, for example, be classified according to their organisational basis into space-based, time-based, feature-based, and combined approaches (El-Geresy and Abdelmoty, 2002). Space-based models include Langran's (1992) temporal raster model, which is an extension of the normal raster model. Time-based models include the snapshot models of Armstrong (1988) and Hunter and Williamson (1990), Hägerstrand's (1970) time cube model, and Peuquet and Duan's (1995) event-based spatio-temporal data model. Langran's (1992) base state with amendment model, Langran and Chrisman's (1988) space-time composite model, and Worboys' (1992) spatio-temporal object model belong among the feature-based methods which are extensions of the traditional vector model. Combined methods, which have two or more organisational bases, include Yuan's (1996b) three-domain model and Peuquet's (1994) triad-model. In the three-domain model the idea is to treat semantic, temporal and spatial objects in three separate domains. The model also dynamically links relevant objects from the three domains to represent a geographic entity or concept. The Triad-model has three views as the organizational bases of the data such as location-based view (where), object-based view (what) and time-based view (when). Mennis *et al.* (2000) have applied Peuquet's triad-model to incorporate cognitive principles into geographical information database representation. In addition to these two early research methods, the combined methods category also includes more recently developed models that are based on object-oriented modelling.

McPherson *et al.* (2004) have also performed spatio-temporal modelling of population locations. They created raster maps of the day- and night- time population, whose aim was to support the evaluation of the damage caused by contaminants that had been spread. In this case the smallest area to which the population numbers can be related is an administrative area. In previous research also Hunter (1994) has used population data on coarser scale of census collection districts. That differs from our case where we use population data that are related to individual buildings.

2.3. Conceptual framework of the study

Figure 1 shows the conceptual framework of our approach to support decision-making by using geographical data, spatio-temporal knowledge and problem-solving models. The structure can be compared with Malczewski´s framework (1999) for spatial expert support system in which he identifies geographical database, model-base, expert system and dialogue system that integrates the user to the computerized system. In our model we use the term "knowledge model" instead of "expert system" and emphasize the temporal dimension of spatial phenomena. This conceptual framework expresses in a squeezed way the general objective of our research, which is to recognize and identify spatial and spatio-temporal knowledge and formulate it into a spatio-temporal knowledge model that can support the decision-making process in an integrated way. In the following the structure of the framework as well as the functionality within it is explained.

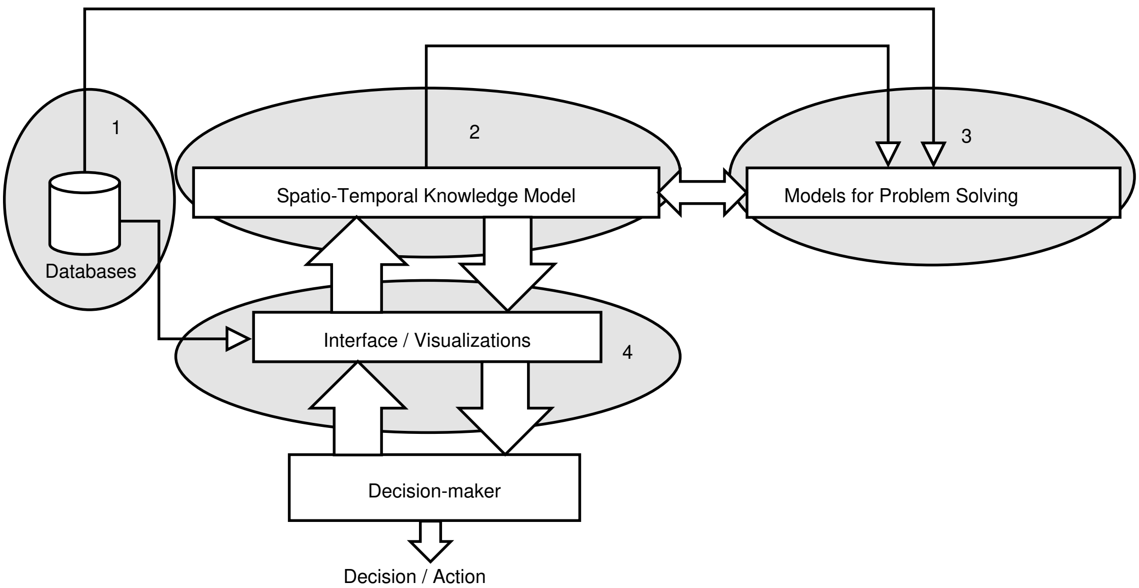

Figure 1. Conceptual framework for supporting decision-making by spatio-temporal knowledge.

In the model we have four main components: (1) the databases, (2) the spatio-temporal knowledge model and (3) the problem-solving models. The user uses all these components via (4) the interface that enables the use of visual and visual-analytic tools. The databases are the regular data sources that are available in the spatial data infrastructure. Databases typically consist of facts, which describe single values, such as basic information or events (Moore, 2000). Problem-solving models are context-related applications like military damage effect analysis model, or fire and rescue risk assessment model aiming to solve a problem that requires both data and knowledge. More generally, problem-solving models can be route optimization, resource allocation or simulation models. Spatio-temporal knowledge model can include any knowledge that is necessary for spatial decision-making. In this application spatio-temporal knowledge is about population dynamics, but knowledge can include any type of human experience or intelligence, for example ontologies. Knowledge is based on human experience and can be represented in many ways. Knowledge can be implemented as separate rule-bases or embedded in the program code in the form of "if-then-else" rules. Knowledge can also be presented as semantic networks showing relations between objects or as frames that allow hierarchies and spatial operators (Moore, 2000). In our application part of the knowledge is stored as rules embedded in the program code, part of the knowledge has been stored in parameter values stored in database tables. The interface component includes visual functionalities as well as visual-analytics tool in which also spatio-statistical tools are included. These tools make the use able to communicate with the system as well as insert his/her knowledge to the system.

The functional idea of the conceptual framework lies in the principles of knowledge creation and collection: knowledge is not created as the last step in the decision-making process but continuously produced by various means and based on various sources. Some basic amount of knowledge must be systematically collected by interviews and questionnaires as well as by adopting experiences from existing documents when the problem-solving models are designed. However, also in this modelling work visual analytics including spatio-statistical methods can be used. The entire process of "decision-making" could be renamed as "knowledge extraction". Instead of trying to make a hard decision the user first becomes familiar with the data available, explores it by using visual and computational tools, learns about the phenomenon, increases his/her understanding about the problem, and finally is ready to make a decision. During the process the user adds his/her knowledge to the system, after using a visual analytic tool new knowledge can be created and this finding can be stored to the system or it can lead into another analysis.

3. Previous work in risk assessment

3.1. The Finnish authorities involved in the project

The Finnish Ministry of the Interior has issued guidelines on systematic risk assessment practice, which state that the preparedness of fire brigades must be based on a municipal risk analysis (Finnish Ministry of Interior, 2000). The definition of the level of preparedness for emergencies in each municipality should be based on a risk assessment process (Lonka, 1999). In the Helsinki Metropolitan area, the fire and rescue services are making operational plans for both normal and unusual (state of war) situations. The interest of the rescue services lies in the enhancement of risk analysis for normal, everyday situations. The Rescue Office of Espoo has developed a GIS application that can be used in order to determine so-called risk zones in any municipality. By using this application the required level of preparedness can be defined, and the requirement for risk assessment can be fulfilled (Ihamäki, 2000). However, the model is considered relatively simplistic as the population data come from the population register, which only provides the address information and does not give a realistic picture of the spatial distribution of the population during the daytime or at weekends. More knowledge about the location of the population is required to support the decision-making.

The Finnish Defence Forces (FDF) is focused on preparedness for wartime situations. The FDF funded a previous research project (called Damage Analysis) in which a GIS application was developed to support the modelling and visualisation of the damage effects of military fire attacks on a built-up environment (buildings) and the population. The aim of this application is to support evacuation and resource planning in any kind of extreme situation. For this application a simple spatio-temporal model of population location was developed (Ahola, 2006). There is special interest at the moment in the FDF in the development of crisis management applications in which the role of interagency operations is essential. It is clear that the development of risk analysis and risk assessment applications related to all kinds of threats against human society should be performed in co-operation between civilian and military organisations.

The core problems in both rescue and military applications related to planning and decision-making lie in the area of risk assessment, including estimating the probabilities and consequences of unwanted events. And in situations where the consequences affect populations, then a special issue that arises relates to the spatio-temporal dimensions of the data. Adding spatio-temporal knowledge to the decision-making increases the quality of the results and makes the risk taken in the decision-making more acceptable.

3.2. The Finnish application for risk assessment in the Fire and Rescue Services

The Finnish application for risk assessment in the Fire and Rescue Services is a simple model based on only three explanatory variables and generalising all kinds of accidents into a single incidence class. The result of the application is a so-called risk zone map in which each grid cell is classified on a risk level from 1 to 4. Risk levels refer to the required preparedness level: the areas of risk level 1 must be reached in less that 6 minutes while for levels 2, 3, and 4 the response time becomes 12, 15, and 20 minutes respectively. Risk levels are calculated on the basis of: (1) the population number; (2) the floor area in square meters, and (3) the number of traffic accidents. Input data, processing, and results use the same 250 m x 250 m grid format. The spatial reference for population comes from the population register, which only provides the residential address of each citizen and does not take into account any activities such as work, shopping, or schooling. The classification of accidents makes the model even simpler, because in the event of only one accident type the risk model actually shrinks to a model of probability. Usually when the risk for any event is calculated, the probability and consequences are taken into account and multiplied according to the basic formula:

$$R = Pr(event) \times C(event),$$

in which Pr(event) is the probability of the event and C(event) is the consequences or cost of the event (Clemen and Reilly, 2001). The consequences of an event can be measured in terms such as buildings damaged or lives lost, and the consequences depend on the magnitude (or size) of the event and the location in which it occurs (Agumya and Hunter, 2002).

In this existing model the probability is calculated by using selected explanatory variables at a specified location. The consequences of the event are not identified and the model only results in an estimate of the relational probability of an accident. The three variables used in calculating the estimate vary according to the space and thus the probability also varies. The results of the application are presented as a risk zone map in which the risk of an incident is visualised using colours. However, the model should be developed further towards an improved risk model by taking into consideration the varying consequences of the different types of accident. The other characteristic of the model that needs to be modified is the need to model changing input information not only spatially but also spatio-temporally. Our research described in this paper deals with these problems, the emphasis being primarily on the spatio-temporal model

4. Materials and methods

In this section we explain the materials and methods used in the modelling process, as well as the basic structure of the model. The data used are primarily basic register data from the SeutuCD data product and other minor data sources. The spatio-temporal modelling methods applied to the problem are selected on the basis of a literature survey, and the software used to create the spatio-temporal model of population location was ArcGIS by ESRI. The Damage Analysis application was programmed with Java programming language supported by ArcEngine library components while the ArcGIS Model Builder tool was employed in processing the primary data to a form suitable for the modelling.

4.1. Data

SeutuCD is a data product developed by the Helsinki Metropolitan Area Council (YTV) containing different data from the whole metropolitan area of the Finnish capital Helsinki (including Espoo, Vantaa, and Kauniainen). In addition to map data, it includes register data, for example about population, businesses and land use. From SeutuCD we used data about buildings and population (according to home addresses), as well as the numbers of employees in businesses and agencies. Although the building data do not contain any population data as such, they were important since they include a classification of buildings according to their use. These were used in order to obtain spatial references for shopping centres, schools, kindergartens, and central traffic buildings. In addition to the SeutuCD data, we used data relating to traffic volumes and the numbers of children in schools and kindergartens, as well as numbers of customers in shopping centres. Table 1 provides a summary of the data used in the modelling as well as its sources, the components of the data and the data types. The study area is located in the centre of Helsinki (Figure 2).

Table 1. Summary of the data used in the project.

Data	Source	Date	Components of data	Data type
Buildings	SeutuCD	2003	location and attribute	Vector: point
Population data related to buildings	SeutuCD	2003	location and attribute	Vector: point
Enterprise and agency data related to buildings	SeutuCD	2003	location and attribute	Vector: point
Person traffic data	City planning department of Helsinki city	1999	location, attribute and time	Vector: point
Shopping centres	Shopping centres	2005	attribute and time	Excel-table
Kindergartens	Social bureau of Helsinki city	31.12.2004	attribute	Excel-table
Schools	School authority of Helsinki city	20.9.2004	attribute	Excel-table
Central traffic buildings	City planning department of Helsinki city	1999	attribute and time	Excel-table

Figure 2. The study area, comprising the centre of the Finnish capital, Helsinki.

4.2. Spatio-temporal modelling methods

Improving applications by adding spatio-temporal model is considered to be one type of spatio-temporal knowledge modelling. The temporal dynamics of population can only be described by collecting knowledge about the daily/weekly activities; this information cannot be called as facts, because a lot of assumptions have to be made. Spatio-temporal dynamics of population can only be treated as knowledge, and based on experience of experts on demography. Technical implementation of spatio-temporal knowledge has no standard solutions, thus a literature search was made. The method selected was rather database management oriented than a typical knowledge representation - instead of for example a rule-based approach a regular database tool was used. The selected technique gives flexibility of updating the knowledge – the user can change the values of parameters and fit the knowledge to his/her own assumptions.

Two spatio-temporal modelling methods were chosen from the literature for adoption in this research project as technical implementation solutions. Langran and Chrisman's (1988) space-time composite model stores time in the same relational table as attribute information. When a change occurs it is stored in a column or row of the relational table. In this case we decided to adopt time as an attribute. This type of data model lacks flexibility since it is necessary to know in advance the number of changes or 'columns' in order to maintain the basic design principle of relational database management system structures. In this case keeping time as an attribute is successful, since we know the number of columns in advance. The space-time composite model was applied to the Damage Analysis application because it is easy for the application to search for the correct value from the column of the relational table. Figure 3 shows the principle of the space-time composite model applied to a spatio-temporal model of population location.

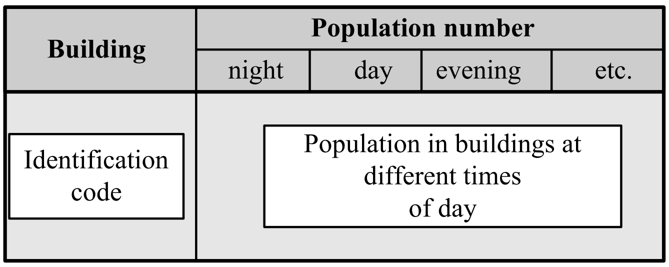

Figure 3. Time as an attribute in the table.

The second model, which was adopted for the research was Yuan's (1996b) three-domain model. Her concept is to treat spatial, attribute, and temporal information in different domains and also to have domain links between different domains. Though Yuan's model was not fully adopted in this research, it gave an idea of how to keep time in a separate relational table. Figure 4 shows a schematic representation of how the three-domain model was applied to this problem. In our case the attribute information contains the total population number in buildings distinguished according to population type. The temporal table includes information about the temporal variation of data stored as percentage values within this parameter table. This type of data model is flexible because it is easy to change the parameters of temporal variation or update the primary data. Of course primary data need processing to attain a form such as that depicted in Figure 4, but not as much as in a space-time composite model.

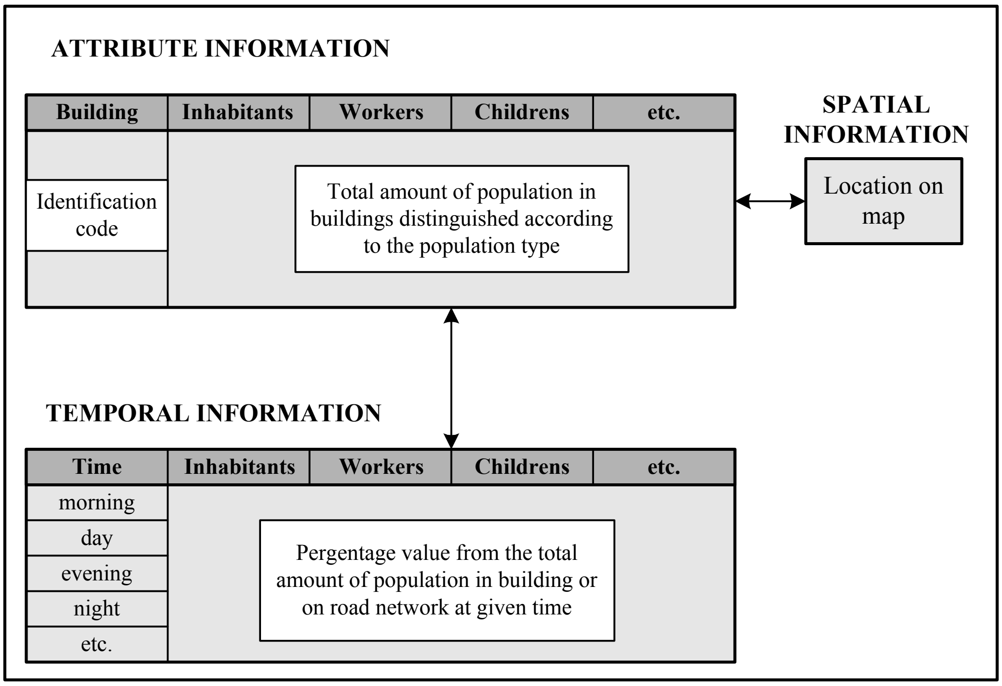

Figure 4. The three-domain model applied to the spatio-temporal model of population location.

The model is in vector format and the population is spatially related either to streets or buildings. The model uses time intervals of a few hours at specific times, such as a weekday night, day or evening. The resolution of the time scale of the model is of the order of a few hours. The total amount of time periods modelled is 14. For every workday there are six time periods and for Saturday and Sunday there are four each. The amount and length of time periods modelled is based on the temporal variation of traffic and shopping centre data. From these data we can perceive morning and evening peak travel hours and classify data according to the diurnal cycle of the population's behaviour, which include for example commuting, working and shopping. Since people's activities on Saturday and Sunday differ greatly from weekday activities the time periods are also different.

Table 2 describes the temporal information table in Figure 4. Population is divided into ten categories, and each modelled time period has an identifier for database searching. Distinction between different population age groups makes it possible to model people's activities differently. We also assume that workers at state or municipal agencies have more regular working hours than private sector workers. Percentage values describe the percentage of the total amount of the population at home, in work, in school, in kindergarten, in shopping centres or in the road network at particular times. Most of the percentage values are based on expert knowledge. Traffic and shopping center data include temporal data, and percentage values in the table have been generalised from that data according to the length of the modelled time periods.

Table 2. Temporal variation of datasets.

ID	Time	Inhabitants (0-14 old)	Inhabitants (15-64 old)	Inhabitants (65-> old)	Workers (state)	Workers (private)	Workers (municipality)	Students	Children	Customers	Traffic
1	weeknight	100	100	100	0	0	0	0	0	0	0,5
2	week morning	80	80	100	20	20	20	5	20	2	6,5
3	weekday	30	30	85	95	95	95	100	100	7	5,5
4	week afternoon	70	50	90	30	40	30	10	20	10	8
5	week evening	95	90	95	0	0	0	0	0	6	5
6	late week evening	100	97	100	0	0	0	0	0	0	2
7	sat. night	100	97	100	0	0	0	0	0	0	1,5
8	sat. morning	100	100	90	0	0	0	0	0	1	2
9	sat. day	90	75	90	0	0	0	0	0	8	5
10	sat. evening	100	90	95	0	0	0	0	0	2	3
11	sun. night	100	97	100	0	0	0	0	0	0	1,5
12	sun. morning	100	97	100	0	0	0	0	0	0	2
13	sun. day	95	95	90	0	0	0	0	0	0	4
14	sun. night	100	95	100	0	0	0	0	0	0	3

4.3. Kernel density estimates

Kernel density estimates have been used in hotspot detection in various fields, such as for crime analysis (Ratcliffe, 1999a). In our case they are used to create the population density maps. Showing densities as a surface can give an efficient visual impression of the spatial distribution of the population density in the study area. The kernel density estimate replaces each point with a kernel, giving the surface a "spatial meaning". The determining factors are the bandwidth (also referred to as search radius) and the grid size. If the bandwidth is too large the estimated densities will be similar everywhere and close to the average population density of the entire study area. Experimentation is required to achieve the optimal bandwidth. An adjustable kernel width, with a wide kernel allowing for higher smoothing, influences the amount of detail in the resulting plot (Silverman, 1986).

A moving three-dimensional function of a specified search radius visits each individual point and calculates weights for each point within the kernel radius, as illustrated in Figure 5. Points closer to the centre receive a higher weight and therefore contribute more to the total density value of the cells.

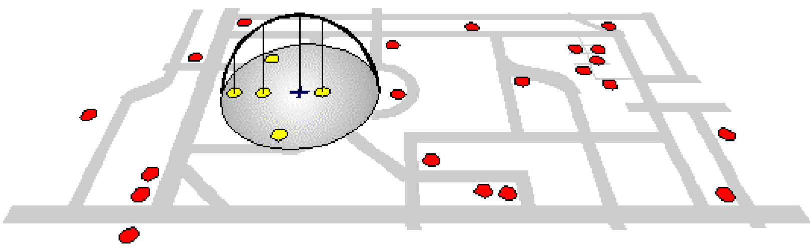

Figure 5. Weight calculation for each point within the kernel radius (Ratcliffe, 1999b).

The final grid values are calculated by summing the values of all circle surfaces for each location. In our case the bandwidth is set to a radius of 100m and the grid size to 25m, which proved to be appropriate settings for the study area. The selection of an appropriate bandwidth is a critical step in kernel estimation and requires testing. The bandwidth determines the amount of smoothing of the point pattern and defines the radius of the circle (centred on each grid cell) containing the points that contribute to the density calculation. A large bandwidth will usually result in a large amount of smoothing and low-density values, producing a map that is generalised in appearance. In contrast, a small bandwidth will result in less smoothing, producing a map that shows local variations in point densities (Bailey and Gatrell, 1995). Kernel-density mapping provides an informative visual analytic tool for learning about the spatio-temporal phenomena, like population and accidents. The user can learn about the spatial or temporal variation. Meaningful variables can be chosen as well as correct hypotheses can be made for further study. Also the final and intermediate results can be effectively presented for decision makers.

5. Results

The spatio-temporal model was applied to the Damage Analysis application and an example was performed with it to illustrate the usefulness of the model in planning and decision-making. In addition, density maps of the population during the day and night were created in order to represent visually the differences between population locations at different times. In this case we created maps only for two time periods but it would be possible to do it to other periods also. Density maps were created to make the outputs of the model more understandable for its users. In both application cases only the population in buildings was taken into account. Traffic data were excluded, although a theoretical solution of the numbers of people on the street network at a specific time was created. It is based on person-traffic numbers, driving speeds, and the length of road segments.

5.1. Damage analysis

In the Damage analysis application, visualisations were used to represent the results and in that way make the analyst's decision-making tasks easier. The purpose of this demonstrator is to support the modelling and visualisation of the damage effects of military fire attacks on a built-up environment (buildings) and the population. The application is useful in evacuation and resource planning for any kind of extreme event.

The use of the Damage Analysis application is to model the bombing of several sites and sum the damages together in order to get a coarse estimate—not to support damage estimates for individual buildings. When several objects are bombed at the same time the errors also tend to compensate each other.

The calculation of damage effects on buildings in the demonstrator is based on a simple damage model (which will be replaced by an advanced one in the real application at FDF). After clicking a bomb to some location, the analyst can choose the bomb type. The program calculates the effects and visualises them as in Figure 6. When we are closer to the impact area the damage incurred to buildings and the population are more severe. The light red circle describes the blast effect area of the bomb and the darker red area is the range of the pressure wave. Damage to buildings is coloured from light blue to dark blue where the darker colour implies more severe damage. Using the dropdown list on the left-hand panel, it is possible to change the time of the analysis. Figure 6 shows examples of night-time and day-time bombing effects. The number of people in the buildings at the time of the event is symbolized within the yellow-green circular symbols. Other symbols represent special objects such as kindergartens, hospitals and elderly citizens' homes, which have special priority when disasters occur. In Figure 6 the red symbols mean hospital buildings and blue one means kindergartens. It is also possible to create a report of the analysis results where damage is distinguished according to building type, and also more detailed information about expected population death and injury is presented. The table works well in conjunction with the visual result, helping analysts in evacuation and resource planning.

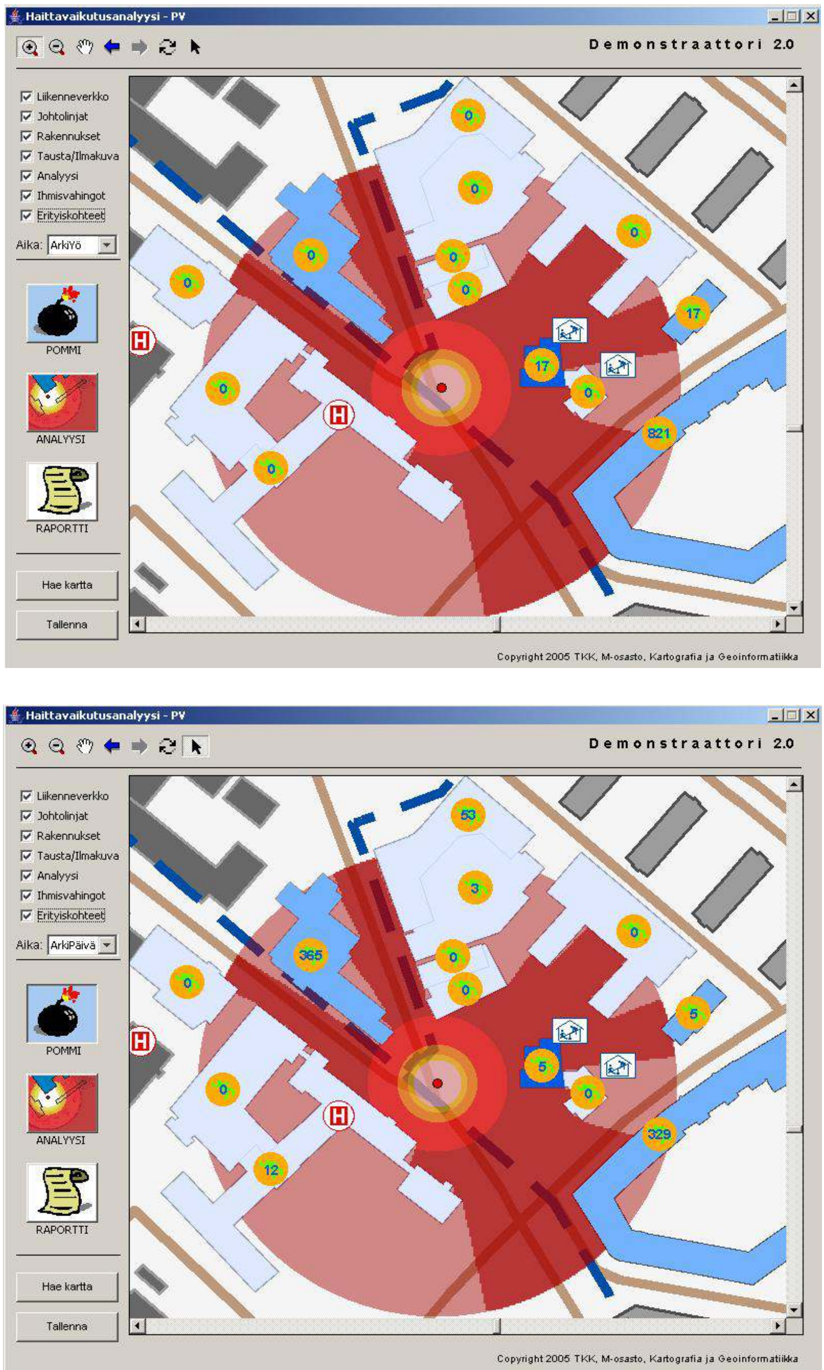

Figure 6. Examples from the Damage Analysis module showing (above) the effect of a night-time bomb blast, and (below) the daytime effect for the same location.

The knowledge for this application was collected from military documentation and expert interviews. For example the damages of buildings are calculated by using the so-called shelter-value of the building. The shelter-value depends on the building material and is made for military applications. It is an example of knowledge that needs to be taken into account. This part of knowledge was embedded to the code by classical if-then-else –structures in code.

In addition to basic interaction techniques such as zooming and panning, analysts can choose which layers are visible in the interface. Even though the interaction techniques in this stage are quite simple, it would be relatively easy to add other techniques such as answering queries related to the analysis results.

An example was performed with the Damage Analysis demonstrator module, where a total of 16 sites were bombed during the night and day. The damage caused was summed together to estimate how many people were within range of the bombs. The result from the example was that at night-time approximately 5000 people were within range and in the daytime approximately 20,000. As we can see, the difference is significant. Based on these results we can also assume that evacuation plans and resource evaluations are more reliable and accurate when a spatio-temporal model of population location is in use.

5.2. Population density maps

Population density maps were created with ArcGIS according to the three-domain model. The kernel search radius was fixed to 100m and pixel size to 25m. Figure 7 presents day-time (9 am to 3 pm) and night-time (12 pm to 6 am) population densities. Low densities are visualised in yellow and high densities in red. It can be clearly seen that the difference between the daytime and night-time population densities is significant.

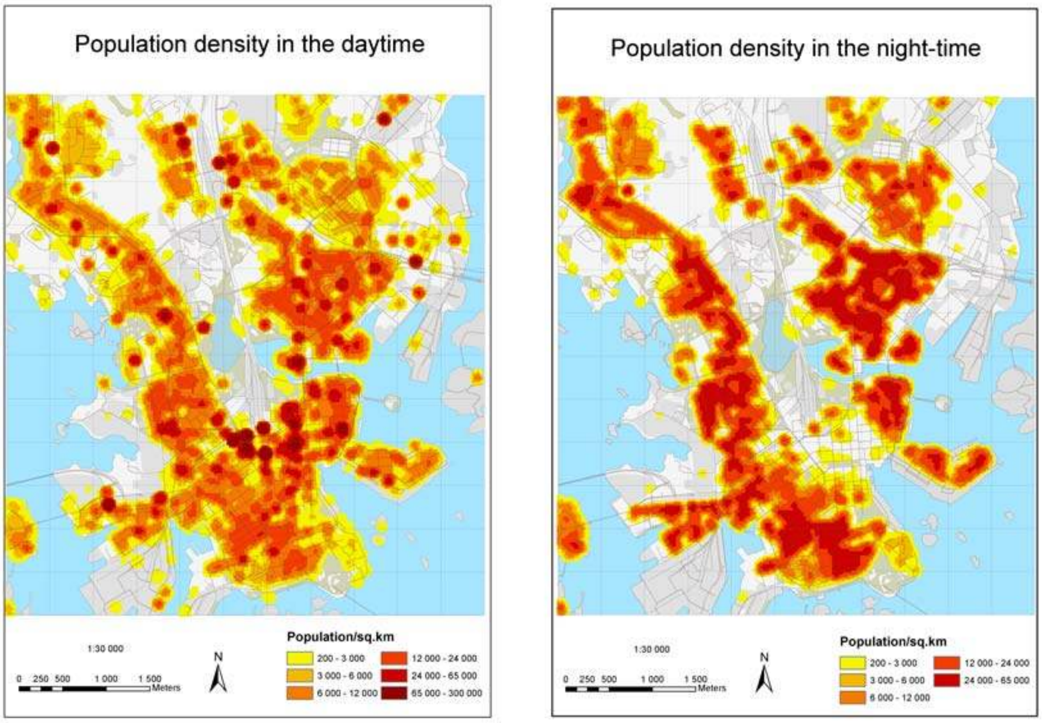

Figure 7. Population densities in the daytime and in the night-time.

The use of colour in map design has been considered in detail by researchers such as Brewer (1994) among others, and applying a colour range can help identify hotspots. While the use of a yellow-red color range has not been formally tested, we informally received positive feedback on the appearance of the maps with the colour settings applied. However, already the first uses of these visualizations among the decision makers gave positive reactions and the role of visual analytics in the development of the model was self-evident.

6. Discussion and directions for further research

In this research we have presented a simple spatio-temporal model of population location and activity, which can be used to improve risk assessment for decision-making and other planning tasks in Finnish fire and rescue services and related military activities. The application example and results show there is need for this kind of model given the variation in population numbers and their locations during the day and night. Clearly, it is essential to have a spatio-temporal model of population location in order to gain realistic estimates of human injuries after a catastrophe, a disaster, or some kind of attack, or to estimate the rescue resources required.

The modelling method proposed here is flexible and adjustable since the temporal information is kept in a separate table from the attribute information. This kind of modelling is enabled by the detailed data available. The quality of the model is difficult to assess because there are many factors that can potentially bring uncertainty to the model, such as uncertainties in the primary data, and errors in the model calculations. In addition, many of the temporal variation parameters have been deduced using a mixture of expert knowledge and common sense, and it is impossible to know how close these values are to reality. In our approach the main idea is continuous knowledge collection, so according to the conceptual framework model whenever the user realizes a need change or add more knowledge, the implementation should allow it. In the existing demonstrator implementation this is only partially possible (for example by changing the parameter values). One of the main issues for our further study is the integrated representation of spatio-temporal knowledge types in one spatio-temporal knowledge model. Definition of the spatio-temporal knowledge types will be the next step towards the integrated model.

On the other hand, while the errors of the model may be considerable when compared with reality, we can say that from the application point of view the resultant accuracy of the model is adequate. In further studies the impact of data quality will be added to the risk model and the relationship between data quality and decision-making based on that data will be analysed. In addition more detailed information about the temporal behaviour of different population groups could also improve the quality of the model. Clearly, the addition of quality considerations will make the results of the research more general and applicable. Instead of one chosen alternative, in many applications like military or civilian crisis management or rescue, the decision maker needs to have several decision alternatives and information about the risk related to each choice. There are cases in which the decision maker is willing or must take even a relatively high risk, as well as situations in which no risk is accepted. The risk aspect has been neglected widely in spatial analysis research field. Some recent publications, however, emphasize the need of risk estimation, like the one on detection and risk for digging activities around underground cables and pipelines (van Oort, 2006).

The Damage Analysis application shows that the model is useful in extreme situation risk analysis. Efficient visualisations help the decision-maker to quickly gain an insight into the prevailing situation. In this phase of the research the application is still quite simple although there are several possibilities for extending the usefulness of the application. For example, other types of disasters could be included in the system, and more detailed investigation of population structures in disaster areas could be made. In addition more advanced interactive analysis methods could be added, such as gaining information about objects directly by clicking on them. For the visualization, also the development of the map symbology and colours is necessary. The symbols need to be quickly and correctly understood, regardless of the professional or cultural background. In multiagency and international projects, like civilian crisis management, this aspect is essential.

The kernel method proves to be a good tool to calculate the population density based on the available data. By creating a smooth representation of density values in which the density at each location reflects the concentration of points in the surrounding area, analysts are able to identify how densities vary across a study area. The overlay of the population density and other background data (such as water areas and roads) can help identify "hotspots" concerning the concentration of people in a particular area at a specific point in time. Population density maps, even animated ones, could be also utilised, for example, in normal condition risk analysis to find a correlation between population densities and accident densities; while visualisations can also be used in testing hypotheses about new explanatory variables in order for the model to be developed further. One idea here would be to create population rasters for different times of the day and study how they could be used to improve the normal condition risk model. We could also examine whether the model is useful in determining optimal sites for service areas, public shelters and fire stations. This kind of visual analytics leads the research to the field of spatial data mining. Our plan is to develop the risk model further and in addition to visualization methods also apply spatial statistics in order to find the correct explanatory variables to the model. Some preliminary studies have already been made (Karasova, 2005) and we are going to continue. When spatial data mining methods are taken into use, vast amounts of spatial data can be processed and even unexpected spatio-temporal knowledge can be extracted.

The population model will be used in the developed risk assessment model for rescue services. It will support the estimation of the consequences of different accidents. The work that has to be done is to define suitable parameters that fit different accidents, such as fires, and modify the model used in the Damage Analysis demonstrator to fit the respective accidents. For example, in accidents related to the transport of explosives or other flammable material, the related incidents can be simulated by using the Damage Analysis model as such.

7. Conclusions

The research described in this paper can be summarised as follows:

1. There is a reasonable indication that the combination of risk assessment concepts, spatio-temporal modelling of population location and flexible representation and visualization can support decision-making in various planning and assessment tasks;

2. The researchers adopted a flexible approach to modelling spatio-temporal location of population;
3. For long-term decision-making purposes the model is a first step towards spatio-temporal risk modelling where the consequences of accidents, as well as the risk related to alternative choices should be taken into account;
4. At this point the model is useful in estimating the consequences affecting people and property after events such as natural disasters; and
5. The generic conceptual model presented in this article gives a framework and a starting point for the further research and development. Integration of spatio-temporal knowledge should be made according to the framework as one and united knowledge model, which is able to intake all kinds of spatio-temporal knowledge and support various kinds of problem-solving models. This research until this shows the necessity and potentiality of such a model. The functional basic principle of continuous knowledge collection and possibility to retrieve and insert knowledge to the knowledge model in any phase in the decision-making including the model design phase has also been verified.

References

AGUMYA, A. and HUNTER, G.J., 2002, Responding to the consequences of uncertainty in geographical data. *International Journal of Geographical Information Science*, **16**, 405-417.

AHOLA, T., 2006, A spatio-temporal model of population location based on people's daily activities. Master's Thesis, Helsinki University of Technology.

ANDRIENKO, N. and ANDRIENKO, G., 2001, Intelligent support for geographic data analysis and decision making in the web. *Journal of Geographical Information and Decision Analysis,* **5**, 115-128.

ARMSTRONG, M., 1988, Temporality in spatial databases. Proceedings: GIS/LIS'88, **2,** 880-889.

BAILEY, T. C. and GATRELL, A. C., 1995, *Interactive Spatial Data Analysis* (Addison-Wesley).

BREWER, C.A., 1994, Color Use Guidelines for Mapping and Visualization. In: A.M. MacEachren and D.R.F. Taylor (eds), Visualization in modern cartography, (Oxford, Pergamon), 123-147.

CLEMEN, R. and REILLY, T., 2001, *Making hard decisions* (Duxbury).

DYKES, J., MACEACHREN, A.M. and KRAAK, M.J., 2005, *Exploring Geovisualization* (Amsterdam, Elsevier).

EL-GERESY, B. and ABDELMOTY, A., 2002, Spatio-Temporal Geographic Information System: A Causal Perspective. Proceedings of the Sixth East European

Conference on Advances in Databases and Information Systems ADBIS'02, LNCS 2435, (Springer Verlag), pp. 191-203.

FINNISH MINISTRY OF INTERIOR, 2000, Kunnan pelastustoimen palvelutasoa koskevat säännökset. In Dnro SM-1999–000939/Tu-31.

FRANK, W.C., THILL, J-C. and BATTA, R., 2000, Spatial decision support system for hazardous material truck routing. *Transportation research,* **8**, 337-359.

HUANG, B., CHEU, R.L. and LIEW, Y.S., 2004, GIS and genetic algorithms for HAZMAT route planning with security considerations. *International Journal of Geographical Information Science,* **18**, 1-19.

HÄGERSTRAND, T., 1970, What about people in regional science? *Papers of the Regional Science Association,* **24**, 1-12.

HUNTER, G.J., 1994, Integrating geographic information systems and telecommunications technology to deliver public safety warnings. *Computer Supported Risk Management*, G.E. Beroggi & W.A. Wallace eds, Kluwer: Amsterdam, 177-94.

HUNTER, G.J. and WILLIAMSON, I.P., 1990, The development of a historical digital cadastral database. *International Journal of Geographical Information Systems*, **4**, 169-79.

IHAMÄKI, V-P., 2000, Paikkatiedot pelastustoimen suunnittelussa. Opinnäytetyö, Pelastusopisto.

JANKOWSKI, P., ANDRIENKO, N. and ANDRIENKO, G., 2001, Map-centred exploratory approach to multiple criteria spatial decision-making. *International Journal of Geographical Information Science,* **15**, 101-127.

JANKOWSKI, P. and NYERGES, T., 2001, GIS-Supported Collaborative Decision Making-Results of an Experiment. *Annals of the Association of American Geographers,* **91,** 48-70.

KARASOVA, V., 2005, Spatial data mining as a tool for improving geographical models. Master's Thesis, Helsinki University of Technology.

KRISP, J., HENRIKSSON, R. and HILBIG, A., 2005, Modelling and visualizing population density for the fire and rescue services in Helsinki, Finland. Proceedings *22nd International Cartographic Conference* (ICC) 2005, La Coruña, Spain.

LANGRAN, G., 1992, *Time in Geographic Information Systems* (Taylor&Francis).

LANGRAN, G. and CHRISMAN, N.R., 1988, A framework for temporal geographic information. *Cartographica,* **25**, 1-14.

LEVINE, N., 2002, CrimeStat: A Spatial Statistics Program for the Analysis of Crime Incident Locations (v 3.0). Houston, Ned Levine & Associates, National Institute of Justice, Washington, DC. Available online at: http://www.icpsr.umich.edu/NACJD/crimestat.html/.

LONKA, H., 1999, Risk Assessment Procedures used in the field of civil protection and rescue services in different European Union countries and Norway. SYKE, Helsinki.

MACEACHREN, A., 2001, Cartography and GIS: extending collaborative tools to support virtual teams. *Progress in Human Geography,* **25,** 431-444.

MALCZEWSKI, J, 1999, *GIS and multicriteria decision analysis* (John Wiley & Sons, Inc).

MENNIS, J. L., PEUQUET, D. J., and QIAN, L., 2000, A conceptual framework for representing complex and dynamic phenomena in geographic information systems. *International Journal of Geographical Information Science,* **14**, 501-520.

MOORE, T., 2000, Geospatial expert systems. In: S. Openshaw and R.J. Abrahart (eds), Geocomputation, (Taylor&Francis), 127-160.

OORT VAN, P., 2006, Spatial data quality: from description to application. Doctoral thesis, University of Wageningen, Laboratory of Geoinformation and remote Sensing, The Netherlands.

PEUQUET, D. J., 1994, Its About Time - a Conceptual-Framework for the Representation of Temporal Dynamics in Geographic Information-Systems. *Annals of the Association of American Geographers,* **84,** 441-461.

PEUQUET, D.J. and DUAN, N., 1995, An event-based spatio-temporal data model for temporal analysis of geographic data. *International Journal of Geographical Systems*, **9**, 2-24.

RATCLIFFE, J. and MCCULLAGH, M. J., 1999a, Hotbeds of crime and the search for spatial accuracy. *Journal of Geographical Systems,* **1**, 385-398.

RATCLIFFE, J., 1999b, *Spatial Pattern Analysis Machine, online user guide.* Available online at: http://jratcliffe.net/ware/spam1.htm.

SILVERMAN, B., 1986, *Density estimation for statistics and data analysis* (London: Chapman and Hall).

SIMON, H.A., 1960, *The new science of management decisions* (New York: Harper & Row).

SINTON, D., 1978, The inherent structure of information as a constraint to analysis: mapped thematic data as a case study. *In Harvard Papers on GIS,* **7**, edited by G. Dutton.

THOMAS, J.J., and COOK, K.A. (ed.), 2005, *Illuminating the Path: The Research and Development Agenda for Visual Analytics.* National Visualization and Analytics Center.

WORBOYS, M.F., 1992, A model for spatio-temporal information. In Bresnahan P, Corwin E, and Cowen D (eds), Proceedings: *The 5th International Symposium on Spatial Data Handling*, 2. San Jose, CA, American Congress of Surveying and Mapping, 602-611.

YUAN, M., 1996a, Temporal GIS and Spatio-Temporal Modelling. In: International Conference/Workshop Integrating GIS and Environmental Modelling, January.

YUAN, M., 1996b, Modelling semantic, temporal and spatial information in geographic information systems. In Craglia M and Couclelis H (eds), Geographic Information Research: Bringing the Atlantic (Taylor and Francis), 334-347.