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A GIS-based urban simulation model for environmental health analysis

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ABSTRACT

This paper introduces an urban simulation model for environmental health analysis (SIENA). SIENA is a novel tool to explore urban interactions and processes with regard to exposure assessments. It is based on urban structures and relationships observed in real-world cities making it a realistic representation of a functioning city. The development of SIENA involved identifying and quantifying fundamental processes and similarities in urban areas in Great Britain and using those to guide the building of SIENA within a GIS. An internal validation confirmed SIENA's realism. Its generality, achieved through the pooling of information from different real-world cities, makes it particularly useful for developing and testing spatial epidemiological concepts and models; simulating processes and interactions relating to environmental exposure; and exploring theoretical and methodological problems in the spatial analysis of environmental health. SIENA ultimately provides a much needed tool in the form of a controlled, simplified urban simulation model.

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Data and software availability

The data described in this paper is freely available for download from the following website: http://www.integrated-assessment.eu/resource_centre/siena_data. The file SIENA.zip contains a collection of shapefiles which can be accessed using common GIS software such as ArcGIS or PostGIS. The different model components consisting of ArcInfo and SPSS scripts can be obtained from the authors upon request. Please contact the corresponding author for any enquirers.

1. Introduction

Urban areas have for centuries been the focus of geographers, sociologists and city planners. Conceptual models have been developed since the late 19th century (von Thunen, 1826) and, over time, they have evolved into sophisticated urban simulations designed to study the evolution and design of towns and cities (Harris and Ullman, 1945), to predict their future development (Fuglsang et al., 2013) or to analyse processes occurring in urban areas (Gaube and Remesch, 2013). The most widely used models today are mathematical models that are based on the formulation of laws that control the behaviour of the system under study; examples include cellular automata (Batty, 2005; Mundia and Murayama, 2010) and multi-agent systems (Semboloni et al., 2004). An interesting alternative provide probabilistic models which assume that the laws driving the model are a set of probabilities. They, thus incorporate an element of chance which introduces a certain degree of error or tolerance into the model. In this sense they are more valuable in suggesting possible outcomes (or the likely range of outcomes) rather than predicting a single, specific outcome. Probabilistic models provide an alternative approach for research areas with many unknowns such as environmental health.

Seventy-five percent of the population in Europe live in urban areas, the majority of those in medium-sized cities between 150,000 and 500,000 inhabitants (UN, 2008). The multiple health risks, to which this large population is exposed, make the urban environment an important research focus for environmental health studies (WHO, 2010). Urban dwellers are under the influence of complex processes at different spatial scales, ranging from individuals, neighbourhoods to the entire city and beyond (Pumain, 2006). Even though some of the most important impacts on the

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environment and on human health occur in urban areas, the causal and stochastic interactions between environmental factors (e.g. temperature, air pollution and noise), social factors (e.g. socio-economic status, education and ethnicity) and their individual and combined influence on human health are only partly understood.

Simulation models offer effective solutions to analyse these complex urban interactions and processes. Simulations are essential concepts for our understanding of reality but are not to be confused with reality itself. Rather they provide a simplified, tangible environment which implements models (e.g. mathematical, statistical or computer models) to explore the behaviour and its consequences of a real-world process or system under a specific set of input conditions (Banks, 1999; Peck, 2008). Every simulation makes, thereby, assumptions and generalisations about processes, interactions and feedbacks in the reality they describe. The legitimacy of these simplifications resonates in the interpretations of the outcome of studies run within the simulation environment. Is the result obtained an inherent feature of the reality or is it due to the simplifying assumptions?

Simulations to date have been used as a basis for supporting environmental health studies and assessments (Eubank et al., 2004) and for informing policy and planning strategies (Cuvelier et al., 2007; Lefebvre et al., 2013). Simulations are particularly powerful when analysing very complex phenomena such as the spread of infectious diseases (Ferguson et al., 2006), to assess activity-based vehicle emissions (Beckx et al., 2009) or to explore the effects of dynamic exposures (De Ridder et al., 2008). This is done mostly using data from real-world urban areas to answer questions specific to a town or city. The lack of understanding of urban area, however, derives in part from the sparseness of available data. Difficulties arise in linking and integrating data from different sources and for different issues (such as transport, population, environmental pollution and health) because of differences in sample design, geographical coverage or timing. As a consequence, Lioy (2010) identified the development of new technologies as one of the main scientific research focuses for future environmental epidemiological studies. He specifically highlights the importance of simulations as a tool to locate and evaluate populations in contact with environmental contaminants and to characterise exposure more accurately in order to reduce and prevent adverse health effects.

In line with Lioy's conclusions, this study developed a spatial simulation model of a 'virtual' urban area as a tool for simulating and modelling processes and interactions relevant for geographical studies of environmental health. The purpose of this **SI**mulation model for **EN**vironmental health **A**nalysis (SIENA) is to provide a user-controlled system in which to develop, test and assess methods and models crucial to explore the effects of environmental risk factors on human health. Particular focus is given to the study of exposures to potentially adverse environmental conditions, the sources and magnitude of uncertainty in studies and how different scenarios or study designs might influence the study outcome. Rather than analysing city-specific problems, SIENA provides a 'laboratory' within which to analyse generic, methodological questions relating to exposure assessments that are faced by the majority of environmental health studies in urban settings.

The approach adopted in the development of SIENA is to sacrifice *precision* for *realism* and *generality* (Levins, 1966) which allows exploring general tendencies, such as the increase or decrease of parameters or the deviation from a certain value. SIENA, therefore, focuses on the qualitative, rather than the quantitative aspects of urban systems. It provides the user with methods and tools to simulate and model processes and interactions relevant for spatial studies of urban environmental health. To make it easily accessible to a wide body of users SIENA was built within a Geographic Information System (GIS).

Generality is aspired by pooling information from a sample of real-world cities to inform the development of a typical urban area rather than building a representation of a specific city. This generalisation of information allows to explore broad trends rather than unique or outlier observations specific to one city. At the same time, SIENA strives to maximise realism by rooting its development on structural and design rules obtained from the statistical exploration of these real-world cities. It was developed probabilistically which has the additional advantage that the uncertainties inherent in environmental data can be accounted for by allowing a range of values rather than a single value.

SIENA offers a novel tool to address some of the fundamental challenges faced by environmental health studies in urban settings. Possible applications of this user-controlled urban simulation model in the context of exposure science and health risk assessment are many. They include:

- the development and testing of new models such as models of pedestrian flow, urban air pollution or micro-environments under conditions that the user can control;
- exploring uncertainties in exposure assessments (e.g. data gaps or the effects of unmeasured processes such as population movements and migration) and assessing their potential influence on the outcome of the analysis;
- research into spatial processes and relationships operating in urban areas relating to environmental health and in how these might be affected by different scenarios (e.g. introduction of congestion charging, change of flight path);
- investigating the possible effects of such policies to show how these might play out across a heterogeneous urban population (e.g. who will gain and who will lose) allowing for the ex-ante assessment of potentially expensive and negative outcomes of policy decisions.

SIENA provides the spatial platform and data infrastructure to support these and other applications. Its pre-eminent strength compared to simulations of real-world cities lies in its flexibility to modify and manipulate the properties and appearance of the urban system (e.g. to alter the spatial pattern of the urban infrastructure, to change the demographic composition, to vary exposure-response functions for specific health endpoints). Without any feasibility restrictions Monte Carlo-type analyses can be conducted by repeated random sampling of parameter values of the urban properties.

2. Methods

SIENA's purpose as a simulation environment to explore urban processes from an environmental and spatial health view is reflected in the data and methods used to build it. To allow maximum flexibility for the user, SIENA is made up of a two-tier data structure consisting of a core structure and contextual information (see Fig. 1).

The SIENA core structure typifies a medium-sized city in Great Britain. It is based on terrain, land cover, transport network and population structures of real-world cities. These four key urban components provide important information for environmental and health analysis because they interact, both with each other and with other, external influences. For example, there is a twofold impact of the terrain on traffic-related air pollution: firstly as a determinant of meteorological conditions (e.g. wind direction) and secondly as an important influence on the spatial distribution of the road network, available building land and consequently population density. Population density is essential to predict population exposures but is also related to urban expansion and determines land cover change mainly from agricultural to urban land use and consequently has indirect influence on the transport system. Particular focus is therefore given to the interactions between these four urban components to preserve in SIENA the complex interactions that can be observed in the real world.

Contextual data is the second component of the SIENA structure. This is scenario-specific data that can be added by the user as the need arises for specific

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