Population 24/7: building time-specific population grid models

David Martin, Samantha Cockings and Samuel Leung
School of Geography, University of Southampton, Southampton, SO17 1BJ, UK
Email: D.J.Martin@soton.ac.uk

Paper presented at the European Forum for Geostatistics Conference 2009, The Hague, Netherlands, 5-7 October 2009

Introduction

Many areas of social science research and public policy rely on small area geographical representations of population. Studies of disease prevalence, crime rates, exposure to environmental hazards, transportation modelling and the more applied challenges of emergency planning, service delivery and resource allocation rely fundamentally on statistics relating to the distribution of population. Grid-based population models have considerable advantages for population representation, offering more meaningful representation of settlement and neighbourhood pattern, including the geography of unpopulated areas, and providing stability through time. As a result, gridded models have seen extensive use where population must be integrated with environmental phenomena (Brainard et al., 2002; Mennis, 2003).

Current approaches to spatial population modelling, whether based on conventional small areas or regular grids, rely almost exclusively on residential locations for the geographical referencing of population, drawing heavily on census definitions of the 'resident population'. There are however, good conceptual and practical arguments for modelling population at different times, incorporating population movements from seasonal to diurnal timescales, so as to predict population exposure to a specific hazard, or potential customer numbers during a working day. This paper addresses these issues by presenting work in progress on a two-year project to develop 24-hour gridded population models of the UK. The project is based on an existing adaptive kernel density approach for building gridded population models (Martin, 1996), which is now being extended to become a spatio-temporal kernel density estimation method. We begin by briefly reviewing space-time population modelling methods, then move to discuss data sources and our modelling approach and conclude with some illustrative results from our initial work.

Space-time population modelling

Time-specific population models have typically been characterised as "daytime" and "night-time" models. Many earlier attempts have been hampered by a lack of appropriate data sources or by overly simplistic temporal characterisations. In response, a generally extensible methodology for the production of spatio-temporal population models is proposed. There are no widely accepted methods for obtaining time-specific population distribution models although the issue has long been recognised as an important challenge (e.g. Schmitt, 1956) and is the focus of several current initiatives. Bhaduri (2008) sets out the basic problem that in most modern societies the locations of residence and daytime activities are generally different and that population measurement systems such as censuses tend to rely almost entirely on a residence base, counting people at their home locations. In some national censuses, supplementary questions relating to place of work (or education) provide an additional insight to the location and travel behaviour of some population sub-groups on certain days but generally we have a far from complete understanding of temporal variation in non-residential population distributions. Ahola et al. (2007) present a temporal model of Helsinki, using moving kernel density estimation for visualization of results on a regular grid. The Landscan USA project (Bhadhuri et al., 2007) is currently developing a major new data resource which will incorporate “daytime” and “night-time” 90m-resolution gridded models of the USA. Obstacles to the realization of more fully-developed time-space population models have included both the relative weakness of GIS software at handling spatio-temporal phenomena and the absence of detailed data on short-term population movements. The most promising methodologies are based on dasymetric and/or gridded spatial representations and the approach proposed here builds on an established population surface modelling methodology, taking advantage of both present and potential future data sources.

Major motivations for seeking to redress this lack of understanding continue to be emergency planning (where the focus has shifted more to assessment of population at risk from environmental hazards and criminal activity) and the commercial advantages to be gained by maximising contact with potential customers. A range of analysts have noted the importance of having realistic daytime population estimates and have developed custom solutions, generally based on daytime and night-time models where a census base is used for night-time and some combination of census data and the relocation of specific population sub-groups forms the basis for the daytime model. Sleeter and Wood (2006) propose a method motivated by the need to have more realistic daytime population estimates for emergency planning. They use US census data for small areas, transferring working populations out of their home areas during the daytime and redistributing these onto a variety of workplace locations derived from a business directory. School populations are similarly reallocated. Their underlying spatial model is dasymetric, based on the intersection of land parcels and census areas but the entire study area is small. McPherson et al. (2006) present a national model for the US using a gridded model. Again the temporal division is into daytime and night-time categories. McPherson and Brown (2004) present static daytime and night-time models by allocating population night-time and daytime residential and daytime employment locations. An enormous proportion of population time is spent in travel, which facilitates the shifts between distributions at different times and McPherson et al. (2006) attempt to model the numbers of people in the transportation system, with particular emphasis on population transfer to hospital following a hypothetical airborne release of a hazardous substance in a densely populated area. Further, given their interest in airborne hazards, their modelling framework includes explicit estimation of indoor and outdoor populations. Smith and Fairburn (2008) provide what in some ways is the most relevant previous UK-based work, although their GIS database approach, undertaken for the Health and Safety Executive, relies heavily on assignment of estimated populations to topographic features, without any unifying spatio-temporal modelling framework. Although some population sub-groups are handled with sophistication, volume preservation at any specific modelled time is not assured.

The relevant temporal framework is of course much more complex than that addressed by contemporary daytime and night-time modelling approaches, an issue clearly demonstrated by Ahola et al. (2007). Overlaid on historical time are complex cyclical timescales which lead to the short-term spatial redistribution of population. These include time of day, day of week, term times, public holidays and seasons. Population is further redistributed temporally and spatially on an ad hoc basis for special events, ranging in scale from local events to the 2012 Olympics.

Data sources

Small area population statistics in the UK are primarily driven by census data and official mid-year estimates (MYEs), with additional sources based on addresses, ground surveys or remote sensing providing indirect estimates of finer-scale residential change. The principal population base for the 2001 census statistics was one of 'usual residence' on Sunday 29 April in that year. Although additional information was captured on workplace addresses, contemporary demographic estimates largely avoid dealing with the complexities of population mobility and essentially present an abstract, night-time distribution of population, associated only with residential address locations.
Existing census datasets do provide some evidence about the locations of population other than usual residences, but this is currently under-utilised with respect to the derivation of dynamic population models. For example, census outputs include workplace population counts and travel to work statistics (and in Scotland, travel to School), although not all members of the population have workplaces and workplace locations do not always equate to respondents' daytime locations. Students are enumerated at term-time addresses and basic counts can be constructed for 'home' addresses.

No fundamental changes to these arrangements are planned for the 2011 UK censuses, but during the 2000s a range of important non-census data sources have become available which provide information about the location of population sub-groups at specific times. Many of these are collated within the national Neighbourhood Statistics Services (NeSS) including MYEs; pupil and employee counts. Others are beginning to be published directly by government departments and other organizations, such as annual employer and employees numbers; an extensive range of average daily and hourly traffic flow data; passenger flows at key nodes of the public transport system; prisoner counts; hospital inpatient and outpatient numbers and museum and tourist attraction visitor numbers. All the above data provide clues to the locations of sub-groups of the population at specific times. Smith and Fairburn (2008) provide a review which covers many relevant data considerations in the UK context.

Datasets which potentially provide the most dynamic population monitoring such as retail footfall counts, mobile telephone service usage or the GPS-based vehicle tracking systems proposed for road pricing purposes are variously commercially sensitive, present considerable geoprivacy challenges or are some years from realisation. There is an obvious extension to the work described here to begin to capitalise on these additional sources, but essentially they represent improvements in granularity rather than fundamentally different data types and they are beyond the scope of the currently funded research project. Even if all these data sources were available now, there is no established integrative framework for modelling time-specific aggregate distributions.

The method proposed here is not based on any new data collection. Rather, we are seeking to utilize the rapidly-growing set of published secondary data sources. The underlying logic is that, after some adjustment for inward and outward visitors, each member of the population is engaged in one principal activity at one location at any one time. The principal activities and their locations can be successively broken down into smaller partitions, as illustrated in Figure 1, which is not an exhaustive list. Proceeding from the left, the entire population, with the addition or removal of visitors to/from the study area, are present either at their residential locations, non-residential locations or in transit.

Conventional census-based population mapping deals only with the first major category. Identification of high quality data sources for of the subsequent partitions would represent an enormous advance in the representation of the population distribution in space-time, but even quite modest levels of subdivision have the potential to offer considerable advances over current mapping approaches which either ignore time completely or get little further than night-time and a problematic "daytime". Each additional data source is regarded as a further piece of evidence which can help in allocating the entire population to the most appropriate spatial location at a given time. While it will never be possible to be exhaustive, the figure demonstrates the magnitude of major population activity that is overlooked by current representations of population distribution based only on residential night-time definitions.

Our initial empirical work has been based on a study area in the southern English county of Hampshire, including the City of Southampton. As the audit of each dataset is completed, we are preparing data for all of England and Wales in readiness for the subsequent modelling stages. Scotland and Northern Ireland are not presently part of the main processing sequence due to some significant differences in the definitions of publicly available datasets, although there is no reason in principle why the approach could not be extended to encompass these countries. We have updated 2001 census-based counts to 2006 by allocating ONS MYEs proportionally to OAs (mean population 297) and postcodes through the NeSS geography hierarchy. It is necessary to use census tables with the fewest cells in order to minimise the most severe effects of the census small cell adjustment methodology (Rees et al., 2005). All our data reconciliation is based on a limited set of principal age-sex groups, determined by the available dataset definitions. The census contains baseline information on 2001 workplace populations which we have reconciled with overall counts from the Annual Business Inquiry (ABI) datasets at ward or LSOA level and reweighted to OA level in order to produce estimated workplace populations by broad industry type for each time period. Most educational establishments from primary schools to universities, together with some age-sex breakdown of student numbers are available through the Neighbourhood Statistics Service and we have augmented this with EduBase independent schools data in order to produce term-time population estimates for all population engaged in education.

We are currently working with further data sources covering hospital inpatient and outpatient numbers (Hosptial Episode Statistics) and a wide variety of other major activity groups, as indicated in Figure 1. It is possible to combine these datasets at different levels of detail, providing that population counts are unambiguously allocated within the branches of the allocation 'tree'. It is also important to note that we are not attempting to model or represent every possible human spatio-temporal activity! The category "generalised local" activity represents the entire range of activities which fall below the spatio-temporal resolution of our datasets or model. These might include activities such as visiting a neighbour, corner shop or family doctor, where the distances and population magnitudes might most reasonably be covered by a simple background value for human activity, for example based on population or business density. In our work to date we have been treating a primary school as a practical guide to the smallest scale to be considered. This equates to a location with a usual population capacity of 200 people on 250 days, or around 50,000 visitors per year.

A significant further area of work relevant to the modelling method described below will involve the creation of a "background" layer which, at a minimum, indicates those cells to which it is valid to allocate population counts. At the simplest level, this should be a mask layer which prevents population from being allocated into e.g. areas of permanent water. It is however desirable to produce a layer which contains some classification of population capacity, such that remote rural areas receive a low weighting while an urban area, motorway or transportation hub would have a very high capacity to receive populations “in transit”. We are currently investigating the most appropriate combination of land use or land cover data, combined with traffic flow and passenger counts.

Modelling framework

The grid modelling method introduced by Martin (1989) and developed in various papers including Martin (1996) and Martin et al. (2000) is one of several approaches available for the creation of gridded population estimates from conventional census data sources. It uses data from population-weighted centroids of small areas, such as postcodes or census output areas, in order to redistribute population into a regular grid by means of an adaptive kernel estimation algorithm. This algorithm focuses on each centroid in turn and undertakes an analysis of local centroid density. The width of the redistribution kernel is adjusted accordingly, so as to represent a circular approximation to the typical areal extent of zones in that locality. A distance decay function is then used to redistribute the population count associated with that centroid into the kernel, accumulating population in the cells of the output grid. A masking grid can be taken into account which restricts the redistribution of counts from a given centroid into a specific geographical area, as discussed in Martin (1996). Some cells, typically in densely populated urban areas, will receive population from several centroids while others, typically in remote rural areas, will receive no population at all. In the past, these input centroids have only ever represented residential population locations and the resulting models have therefore been an approximation to a conventional “night-time” population distribution at the date of the census or population estimate. In this approach, in common with almost all other conventional mapping methods, the entire population is assumed to be represented by the sum of the input spatial units and the question of the temporal provenance of the model is not explicitly addressed. This algorithm has most recently been implemented in Microsoft Visual Basic 6 as the SurfaceBuilder program, which can be downloaded from http://www.public.geog.soton.ac.uk/users/martind/davehome/software.htm. If the facility exists to pre-structure the input data to represent population at all centroids relevant to a particular time and date (i.e. those representing not just residential locations but all locations of human activity), then the present software will produce a reasonable approximation to the population distribution. This approach has been followed in order to test the preliminary datasets and as a means of evaluating some of the modelling concepts being developed here. There are however several important deficiencies of this approach, not least the need to produce a separate cut of the entire database for each different time to be modelled and the absence of any conceptual or practical mechanism for handling the large population in transit between centroid locations at a particular time.

The spatio-temporal version of the model is currently being developed to accept centroid locations, each of which is associated with a temporal profile describing the presence of population at different times. A first stage is to identify the target time and study area and to make any necessary adjustments for inward and outward external visitors based on interregional and international passenger estimate applicable to the date being modelled. Each data location is described in terms of a usual population capacity and a time profile, indicating the proportion of the capacity population that is present at any given time, and additional data about its “region of influence”, representing the extended area over which people may be travelling in association with that location. The spatial extent may either be a single point (for example representing a single building or establishment) or a redistribution kernel, to be treated in the same way as in the existing method. Thus population present at a primary school may be allocated to a single coordinate location without redistribution while the population present in a residential census output area would be treated as in the current model. The numerous new data sources described above provide potential inputs to this modelling framework with the very important condition that they are associated with specific time provenance data and regions of influence. In some cases, these are known with a moderate degree of exactitude (such as length of school day, school term dates and catchment areas), while others can be estimated with varying degrees of precision according to the specific source (such as the number of visitors to the British Museum on a Saturday and their region of origin derived from visitor surveys). Seasonal, term-time, weekly and daily time cycles can all be incorporated within such a framework and models can in theory be constructed for any time. The temporal and spatial information interact in so far as the spatial range of a centroid will vary according to time – for example, a school will generate most activity in its area of influence at the beginning and end of the school day. All centroids thus have spatial and temporal ranges, such that populations can be assigned to residential (e.g. census areas) or non-residential locations (e.g. schools, workplaces, etc.), according to the distribution of population at that time. It is important to recognise that there is no attempt here to model individual activity patterns or transportation flows. The general approach is entirely extensible to accommodate further data series which may become available in future, but the underlying method is derived from population mapping methods and remains the allocation of the entire population onto spatial locations most appropriate to the time being modelled. The method must thus retain the volume-preserving characteristics of the original algorithm.

Elements of the new algorithm are currently being programmed and tested. Centroids are divided into “source” centroids (for the most part the same as residential centroids in the current approaches), the sum of which defines the total population available for allocation and all other “destination” centroids which may contain non-zero populations at certain times. The sequence of operations involves visiting each centroid in turn and interrogating its time profile and capacity in order to establish the population demanded at that centroid or travelling within its area of influence at the specified time. The earlier spatial redistribution method is then applied to these data, covering both the area of influence and the present population. The new code is being implemented in the .Net framework.

Each of the aggregate datasets is being recast or reweighted onto centroid locations if these are not available from the original source. In the UK, these are most often census output areas or unit postcodes, whose relationships with many other spatial units are recorded in the continuously-updated National Statistics Postcode Directory. Temporal profiles and areas of influence are being established for each centroid type from a range of documentary sources. Some, such as school and college student numbers, opening hours, and catchment radii are relatively simple approximations, while time profiles of employment and distances of travel to work in different industries can be estimated from census and survey sources such as the national Quarterly Labour Force Survey. Thus the workforce present at (e.g.) a catering and entertainment centroid would receive a completely different time profile to that in an educational institution. Generalised time profiles are initially being allocated to all centroids of the same class (e.g. all primary schools having the same term dates and working day) although there is indefinite scope to make these more specific as and when appropriate data sources become available.

Early results and conclusion

At this relatively early stage in the project, effort has been focused on developing the conceptual model, programming tools and datasets required. We have begun by using the existing SurfaceBuilder software to model the south Hampshire study area and to validate the numerous datasets available. While the overall objective may seem enormously ambitious, we have not encountered any fundamental obstacles which suggest that the general modelling framework cannot be achieved. The addition of further datasets and better measurements of different population activities is readily accommodated as long as the hierarchy of Figure 1 is observed and the total population is only allocated once, hence the importance of volume preservation. Figures 2 and 3 illustrate early results from this work, representing population densities of the Southampton region for four reference times on a typical weekday in 2006 during school and university term-time at 200m cell resolution (Figure 2), particularly demonstrating the spatial redistribution of population from residential areas to business and education clusters. Recall that this static approach to the modelling does not currently incorporate any population in transit between locations. The four maps show the daily redistribution of population from an entirely residential (02:00) pattern, through the arrival of early workers at industrial and city centre workplaces (08:00), the daytime distribution with major population shifts to schools, colleges, universities and office workplaces (09:00) and the early evening pattern in which students and many workers have returned to residential locations (18:00). We are also actively exploring the use of 3D block models and shaded polygon maps, overlaid in Google Earth (Figure 3), which combined with time slider tools can provide a powerful visualization option for exploring time-space population distributions in regional-level datasets, as the user is able to "play" and explore a sequence of time-stamped models against the background of a familiar interactive mapping environment. The project website will continue to be updated as the work progresses and can be accessed at http://www.southampton.ac.uk/geography/research/rssa/pop247/index.html.

References

Ahola, T., Virrantaus, K., Krisp, J. M. and Hunter, G. J. (2007) A spatio-temporal population model to support risk assessment and damage analysis for decision-making. *International Journal of Geographical Information Science* 21, 935-953

Bhaduri, B. (2008) Population distribution during the day. In Encyclopedia of GIS Shashi Shekhar and Hui Xiong (Eds) pp. 880-885 Springer

Bhaduri, N., Bright, E., Coleman, P. and Urban, M. L. (2007) LandScan USA: a high-resolution geospatial and temporal modeling approach for population distribution and dynamics. *Geojournal* 69, 103–117

Brainard, J. S., Jones, A. P., Bateman, I. J., Lovett, A. A. and Fallon, P. J. (2002) Modelling environmental equity: access to air quality in Birmingham, England *Environmental and Planning A* 34, 695-716

McPherson, T. N. and Brown, M.J. (2004) Estimating daytime and nighttime population distributions in U.S. cities for emergency response activities. Presented at Symposium on Planning, Nowcasting, and Forecasting in the Urban Zone, Seattle: American Meteorological Society http://ams.confex.com/ams/pdfpapers/74017.pdf

McPherson, T. N., Rush, J. F., Khalsa, H., Ivey, A. and Brown, M. J. (2006) A day-night population exchange model for better exposure and consequence management assessments. Presented at the Sixth Symposium on the Urban Environment, Atlanta: American Meteorological Society http://ams.confex.com/ams/pdfpapers/105209.pdf

Martin, D. (1989) Mapping population data from zone centroid locations. *Transactions of the Institute of British Geographers* NS, 14 (1), 90-97

Martin, D. (1996) An assessment of surface and zonal models of population. *International Journal of Geographical Information Systems* 10 (8), 973-989

Martin, D., Tate, N. J. and Langford, M. (2000) Refining population surface models: experiments with Northern Ireland Census Data. *Transactions in GIS* 4 (4), 343-36

Mennis, J. (2003) Generating surface models of population using dasymetric mapping. *The Professional Geographer* 55, 31-42

Rees, P., Parsons, J. and Norman, P. (2005) Making an estimate of the number of people and households for Output Areas in the 2001 Census *Population Trends* 122, 27-34

Schmitt, R. C. (1956) Estimating Daytime Populations. *Journal of the American Planning Association* 22, 83-85

Sleeter, R. and Wood, N. (2006) Estimating daytime and nighttime population density for coastal communites in Oregon. Proceedings of the Annual Conference of the Urban and Regional Information Systems Association

Smith, G. and Fairburn, J. (2008) Updating and improving the National Population Database to National Population Database 2. Research Report 678, London: Health and Safety Executive

Figure 1: Indicative mapping of total population to activities/locations and association with potential UK data sources

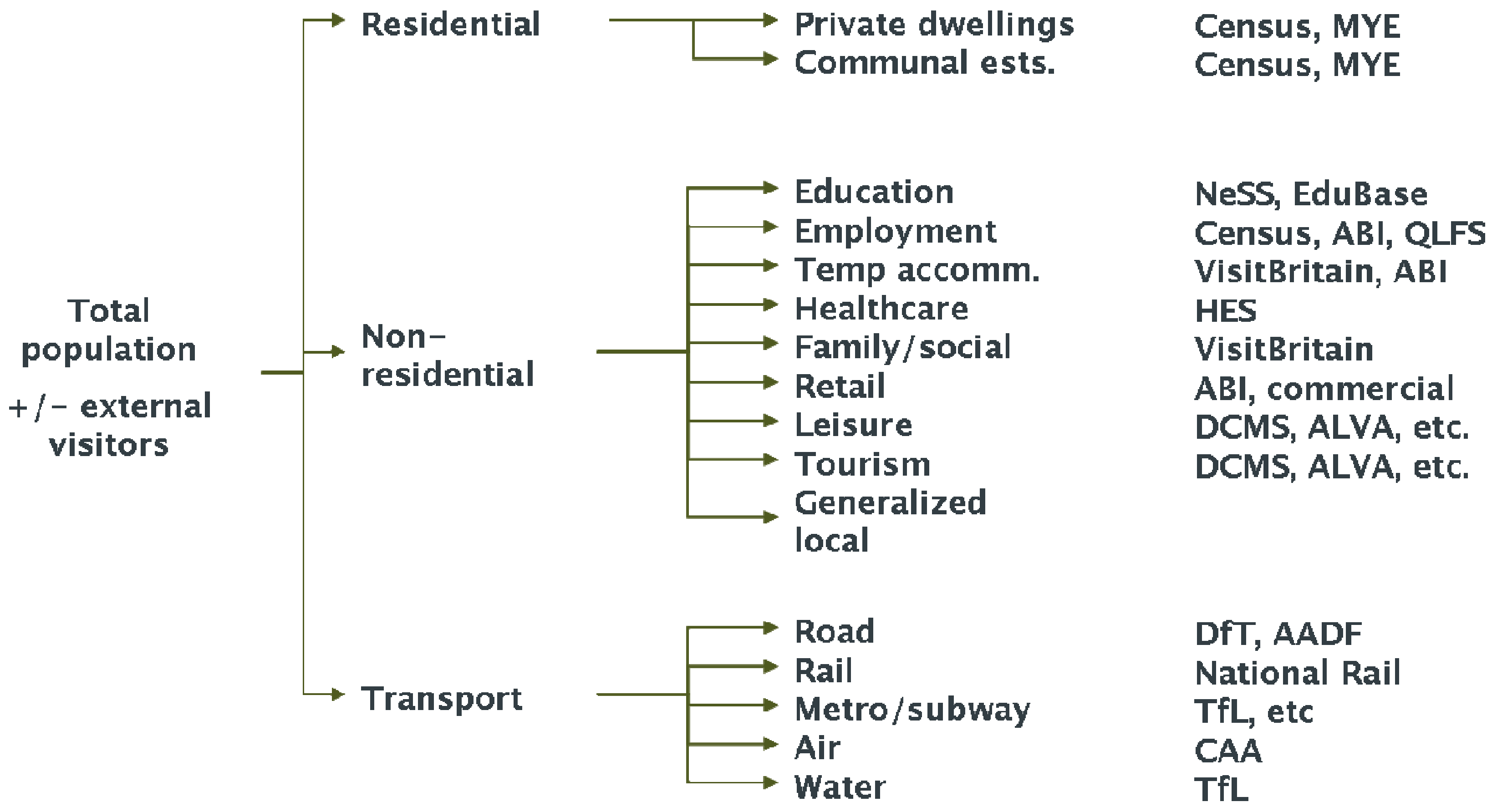

Figure 2: Gridded population models for the Southampton, UK region on a weekday in 2006 (25 x 25km test region, 200m cells) Dark shading: higher density

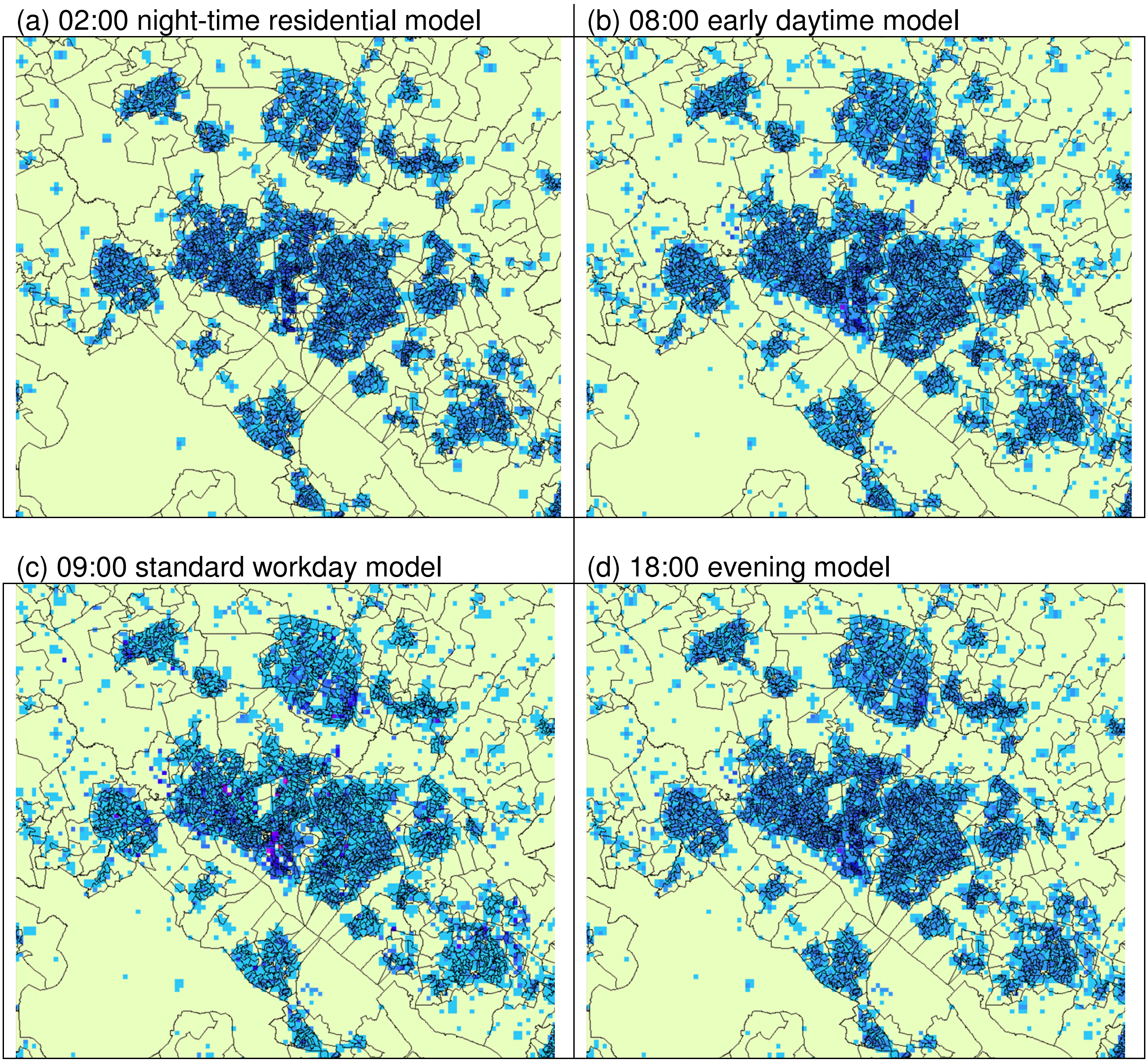

Figure 3: Preliminary daytime population model of the Southampton region, rendered as a 3-dimensional kml layer and overlaid in Google Earth.

Acknowledgement and data sources

This research is supported by Economic and Social Research Council Award RES-062-23-0081. Employee data from the Annual Business Inquiry Service, National Online Manpower Information Service, licence NTC/ABI07-P3020. Office for National Statistics 2001 Census: Standard Area Statistics (England and Wales): ESRC Census Programme, Census Dissemination Unit, Mimas (University of Manchester). National Statistics Postcode Directory Data: Office for National Statistics, Postcode Directories: ESRC Census Programme, Census Geography Data Unit (UKBORDERS), EDINA (University of Edinburgh). Quarterly Labour Force Survey, Economic and Social Data Service, usage number 40023.