A SPATIAL MICROSIMULATION APPROACH TO LAND-USE MODELLING

Olga Feldman[#], Dimitris Ballas[%], Graham Clarke*, Phil Gibson*, Jianhui Jin*, David Simmonds[#] and John Stillwell*

* School of Geography,
University of Leeds,
Leeds LS2 9JT,
England
Tel: +44 113 3433323
Fax: +44 113 3433308
E-mail: g.p.clarke@leeds.ac.uk
p.d.gibson@leeds.ac.uk
ced1j2j@leeds.ac.uk
J.C.H.Stillwell@leeds.ac.uk

[#] David Simmonds Consultancy
Suite 14, Millers Yard
Mill Lane
Cambridge
CB2 1RQ
Tel: +44 1223 316098
Fax: +44 1223 313893
E-mails: olga@davidsimmonds.com
dcs@davidsimmonds.com

[%] Department of Geography,
University of Sheffield,
Winter Street,
Sheffield S10 2TN,
England
Tel: +44 114 222 7923
E-mail: d.ballas@sheffield.ac.uk

Abstract: This paper provides an initial outline of the household location modelling project which the UK Department for Transport has commissioned as part of longer-term research into the factors underlying the demand for transport and the consequences of transport change. The potential of spatial microsimulation to model the impacts of demographic and socio-economic changes, as well as changes in housing supply upon transport flows in West and South Yorkshire and the East Midlands is discussed. It is argued that the approach that is adopted can be beneficial both in modelling terms and in allowing us to draw upon work done by demographers, geographers, economists. Moreover, it is argued that the modelling work presented here has an important potential to contribute to understanding the consequences of planning policy and to forecasting the impacts of possible future policies.

The household location modelling project is being carried out by a consortium consisting of David Simmonds Consultancy, the University of Leeds School of Geography, MVA Consultancy, Professor Roger Mackett (University College London) and Mr Peter Headicar (Oxford Brookes University).

Keywords: household location, spatial microsimulation, transport, land-use modelling, demographics

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1 INTRODUCTION: THE SCOPE OF THE RESEARCH

This paper provides an initial outline of the household location modelling project which the UK Department for Transport has commissioned as part of longer-term research into the factors underlying the demand for transport and the consequences of transport change. The model is primarily intended to forecast "household location" in the broad sense of predicting the future numbers of households living in each zone of a study area, with sufficient detail of household and household member characteristics and choices to predict household population (by age and sex) and car ownership. In addition it is expected to forecast, for persons of working age, whether they work, and if so, where.

Such forecasting has to take account of "household location" in the more specific sense of households choosing where to live, at both local and longer-distance scales. It must also consider all the other processes which change household composition in each place over time, from the simple (e.g. the ageing of each individual) to the complex (the formation and dissolution of households as couples or other groupings join and separate).

In addition to the core modelling of households and their members, the model also has to take account of

- the transport system, and its impact on accessibility and hence on households – this is of critical interest for DfT;
- changes in the number and distribution of workplaces; and
- changes in the supply and characteristics of housing.

The changes in workplaces and in housing must not only be input as possible influences on households, but must also respond to the forecast changes in household numbers and characteristics. Hence, for example, the model is expected to forecast

- how firms respond to changes in the location of households, e.g. service jobs tending to follow households;
- how developers respond to changes in demand, e.g. by seeking to build more houses in areas of faster-rising prices, subject to the constraints or encouragements of the planning system.

The model is not however expected to deal with the feedback from household location to travel demand, i.e. it is not expected to model the travel that households generate. (As part of the modelling of whether and where people work, we will necessarily forecast "who works where", but we will not turn those into actual trips by mode, etc.) The project is therefore not setting out to develop a full land-use/transport interaction (LUTI) model, though the new household modelling developments should be compatible with eventual extension to full land-use/transport interaction. The treatment of transport, housing supply and employment location within the project are intended to be based as far as possible on previous modelling work and not to be the subject of new research. In particular, the household location project should try to avoid overlap with the parallel DfT project on business location, whilst seeking to ensure maximum consistency as a basis for future integration of the household and business modelling.

2 MODELLING TECHNIQUE

The microsimulation technique is used here. In choosing this path we are following the examples already offered by other leading models such as IRPUD (Wegener, 1982), MASTER (Mackett, 1990, 1992, 1993), UrbanSim (Waddell, 1998; Waddell *et al*, 2003) and the TLUMIP system (Upton, 2003; Hunt et al, 2004). The reasons these modellers have adopted this approach include

- the possibility of relating to the range of other microsimulation work on household and individual change over time;
- the problems that arise, both conceptually and practically, with econometric models where a moving household will be distributed in small fractions across many locations – it is much easier to design and build a model where one household moves from one initial location to one new location;
- the possibility of building explicit consideration of available information, information-gathering and search processes into microsimulation; most practical forms of econometric choice modelling (i.e. logit models) assume perfect knowledge of all available alternatives.

Microsimulation involves modelling the choices and changes of a large sample of individual households and household members, considering the members of the sample one at a time and predicting a specific outcome for each choice or change for each member. This contrasts with conventional "aggregate" modelling, which considers all the households in a particular category, and predicts what proportion of them will make each choice.

It has been recognized for some time that microsimulation offers substantial advantages in terms of the ability of the model to represent the wide range of household characteristics and circumstances. This applies in particular to taking account of the wide variety of individuals who may be present within households of the same composition. In addition, microsimulation offers possibilities of representing the ways in which households behave in accordance with "rules", or the ways in which they search for information (e.g. on available dwellings) before making decisions, which are infeasible with conventional modelling techniques.

Microsimulation does however raise significant challenges. These fall into two categories: the assembly of the initial database, and the operation of the model. A detailed database contains information about each of the individuals in the household and their inter-relationships, about the characteristics of the household as a whole (e.g. car ownership and dwelling tenure), and about their dwelling itself. In theory, the data collected in any of the recent Censuses could yield such a database. In practice, the restrictions on the release of Census data mean that it is not possible to obtain such a database directly. A lot of effort (in the UK and elsewhere) has therefore gone into developing methods of creating synthetic sets of household/person data which are consistent with published Census tables at a small area level (Ballas et al., 2005).

Another aspect of this research effort has been in developing methods of combining data from different sources into the generation of the individual household/person database, so as to add data which is not collected by the Census. Applications of this include adding additional detail about household/personal histories, or about the household's ownership of various water-using items such as washing machines and dishwashers (as part of a model of water consumption).

The operation of household microsimulation models takes a number of forms. Some are static and involve using a fixed sample of households and household members to predict how modelled aspects of behaviour would change under different circumstances (Hancock and Sutherland, 1992; Harding, 1996; Mitton, Sutherland and Weeks, 2000). Other models serve mainly to synthesize new future household/population datasets controlled to independently forecast totals (Ballas et al., 2005). The most complex forms involve modelling how each household will change over time and the different choices which the household and its members will make during each period (Mackett, 1990; Hunt, 2004).

The present project intends to pursue this last form, which was successfully implemented in MASTER. The intention is therefore

- to synthesize an initial household/person database, and then
- to model the changes to this set of households and persons (including the dissolution and formation of households) over time in a way which will allow the "histories" of households to be recorded and, ultimately, tested against data which records such histories (such as the British Household Panel Survey (BHPS)).

The changes to be modelled can usefully be split into "choice" and "non-choice" processes. "Choice" processes are those where we are interested to model the household's or individual's choice at least in terms of the alternatives they consider and the variables which influence their decision. The "choice" processes modelled clearly have to include location and relocation, since these are central to the model.

"Non-choice" processes are those where – for the purposes of this model – we are content to assume a fixed set of probabilities or rules to determine the outcome. Ageing is the ultimate example of something which is truly a "non-choice" process, in that nothing an individual does can influence it. Marriage is a good example of something which is – for most people – a choice but which will be treated as a "non-choice" process in the model, since for this project we are not particularly interested in why people decide to marry or whom they choose to marry – it is sufficient to model that a proportion of people in certain group do marry, and to join them with an appropriate partner.

Both "choice" and "non-choice" processes involve changes where what is input, or forecast, consists initially of the probability that a particular outcome will arise for a given household or person in the sample. A simple example is the probability that a childless woman of a given age, marital status and education will give birth to her first child during the next year. The standard method for converting such a probability into a specific outcome for an individual woman in the sample is Monte Carlo simulation (MCS). In the simplest case of a yes/no outcome, the MCS procedure is

- find the probability of the positive outcome – for example, it may be input that a woman of a given age and marital status has a 5% probability of a giving birth in one year;
- the computer generates a random number in the range 0 to 1;
- if that random number is less than the probability (in our example, less than 0.05) then model the positive outcome (this particular woman does give birth to a child or children) and follow through the consequences (add the resulting child(ren) to the database as persons in the same household); otherwise model the negative outcome (no child).

The important feature is the use of the random number to determine the outcome for the individual member of the sample. When this process is applied to a large sample of women with the same 5% probability of giving birth, then the model is highly likely to predict that 5% of them will give birth. For small samples, such as the number of women of a particular age in a single ward, it is highly likely that many of the results will be substantially different from 5%. Such variations do of course occur in real life. What complicates the simulation process is that any one run of the model represents only one example of the possible outcomes. Unless the process is deliberately constrained, MCS processes produce different results each time the model is run. A sequence of runs will produce a distribution of results. Methods of dealing with these distributions are needed for interpretation of the results, especially in model validation.

3 DESIGNS FOR THE MICROSIMULATION COMPONENTS

The different processes of change that need to be represented can generally be grouped into

- individual demographic processes (ageing, death/survival, giving birth);
- household formation/reformation (beyond the changes in household composition resulting from individual processes);
- relocation of existing households, and location of new/in-migrant households;
- changes in employment status and location (and hence commuting).

Most or all of the existing spatial models which treat household changes explicitly represent essentially these groups of processes. They generally apply them in this order, reflecting the hypothesis that the changes later in the list are more dependent on the early changes than vice versa. They add varying degrees of complication especially in the later stages (particularly to do with the linkages between change of individuals' employment location and change of household residential location).

Figure 3-1 shows the process as working through all the processes for each household in turn, on (implicitly) an annual cycle. We arrange the process so that, for example, the location/relocation process can take account of all households, since households wishing to leave their present dwelling are a major source of housing supply. All of the individual and household formation processes, including possible out-migration, are run to the point where there is a set of potential movers to consider, and then the location/relocation model is run. The households and population are accumulated in their new locations, and local job search is modelled.

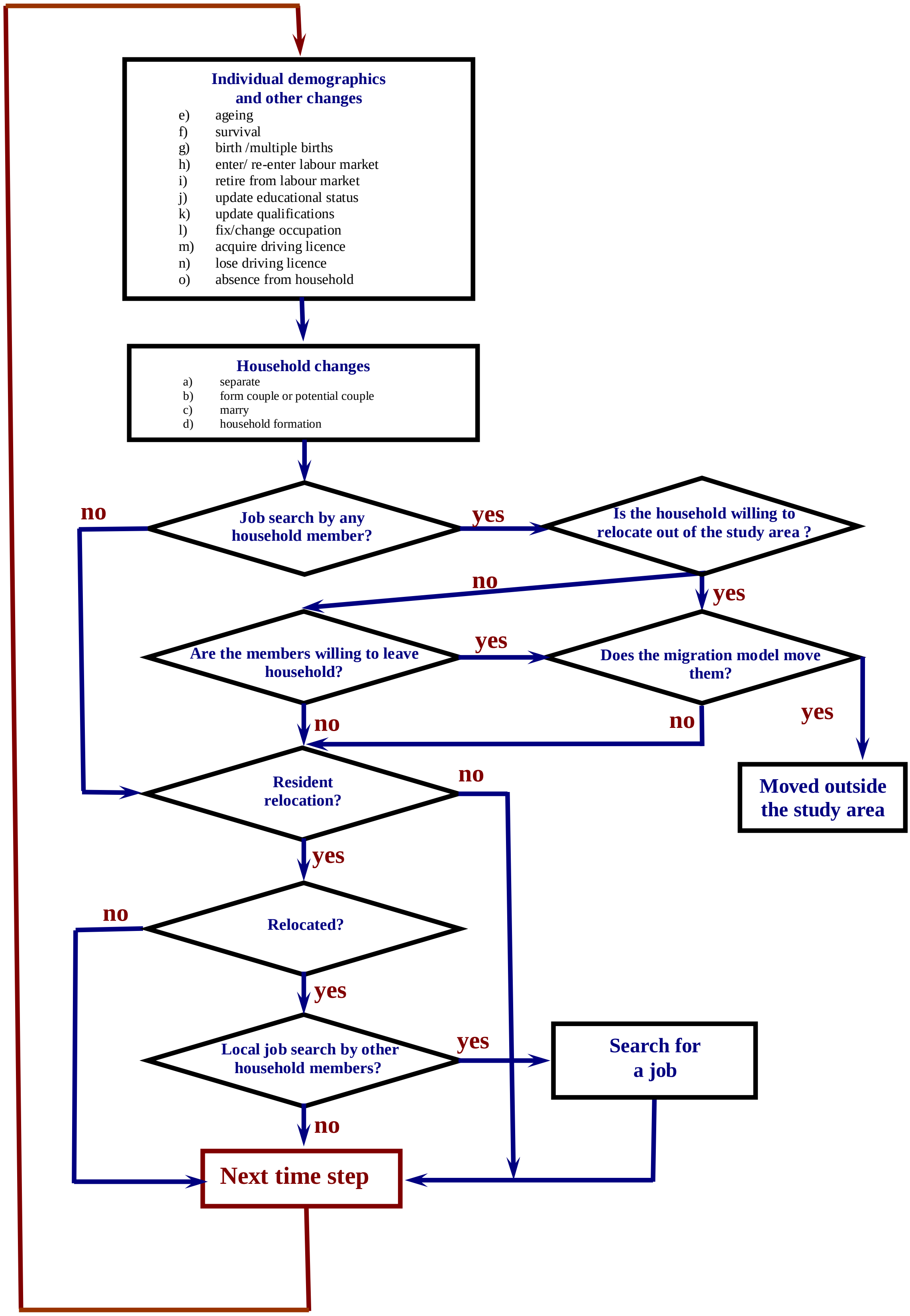

Figure 3-1 Possible sequence of model components

Previous work conducted at the Universities of Leeds and Sheffield (Ballas and Clarke, 2001; Ballas et al., 2004) is particularly important in providing tools to create the initial microdata sets, whilst the processes in MASTER (Mackett, 1990) provide the starting point for the dynamic modelling. The DELTA package and its existing application to South and West Yorkshire (Simmonds and Skinner, 2004) will be used to provide aggregate modelling of non-household elements (e.g. employment and housing change), and the existing transport models from the same study will be used to provide inputs to accessibility calculations.

4 DATA SOURCES

There are a number of geographical and non-geographical datasets that can be used by a spatial microsimulation model. In this section we outline the sources of data that are useful in the context of this project, in particular the datasets that become available every 10 years from the Census of Population returns, as well as the British Household Panel Survey and the ONS Vital Statistics.

The UK Census of Population has been and remains the most authoritative social accounting of people and housing in Britain and is a unique source of data for the social sciences (Dale, 1993; Rees et al, 2002). The Census records demographic and socio-economic information at a single point in time and is normally carried out every ten years. Census datasets describe the state of the whole national population and are extremely relevant for the analysis of a wide range of socio-economic issues and related policies. The topics covered by the Census are determined, amongst other factors, by the necessity to preserve comparability over time and the need for timeliness (Dale, 1993). The most recent census in the UK was held in April 2001.

Population individual level data or microdata are an invaluable resource for social science research. Compared to aggregate tabular population data, population microdata contain much more detail on household or individual attributes, but are released at a coarser geographical level. The growing need for population microdata has led an increasing number of governments to commit to the decennial production of census-based microdata samples. In Britain, the release of microdata files had been under discussion since the 1970s and after a detailed assessment of the likely risk to confidentiality the UK Census offices agreed to release Samples of Anonymised Records (SARs) from the 1991 Census of Population (Marsh and Teague, 1992; Marsh, 1993; Middleton, 1995). In particular, two samples were extracted:

- A 2% sample of individuals in households and communal establishments, comprising 1.1 million records that contain information on all the topics asked in the census and limited information about other members of the household.

- A 1% sample of households and individuals in those households, comprising 215,000 households and the 542,000 individuals enumerated in them (Dale *et al.*, 2000).

However, one of the major limitations of Census microdata is that they are constrained by the number of questions asked in the Census.

Data from the British Household Panel Survey (BHPS) was also used in the context of this project. The BHPS is an annual panel survey of the adult population of the UK, drawn from a representative sample of over 5,000 households. The aim of the survey is to deepen the understanding of social and economic change at the individual and household level in Britain, as well as to identify, model and forecast such changes and their causes and consequences in relation to a range of socio-economic variables (Taylor *et al.*, 2001).

Further demographic data is accessible through ONS and Essex Data Archive sources. Mortality counts and rates by age and gender are available from these sources, but are consistent in assuming a base format of grouped ages. In order to create a working model from this data we attributed mortality rates to individuals on the basis of the standard mortality rate (SMR) for their age range. Another data complication here is the intention to incorporate adjustment for mortality by socio-economic group. This action is necessary to reduce generalization and increase the realism of our model. Although a combinatory dataset reflecting all of these requirements has not been forthcoming, we adjusted probabilities for known mortality rates by socio-economic group using crude 1991 statistics.

Birth rates (or fertility data) have also been sourced from ONS and the Essex Data Archive. To establish a working model, we assumed rates apply to the individual based on the age group into which they would be classified. Information on birth rates relative to parents' marital status and number of previous children have been retrieved from ONS sources and will be incorporated into the model through direct data links or weightings. In addition, we have also derived fixed probability for gender of live births and the likelihood of multiple births (e.g. twins) from Birth Statistics FM1 data at ONS.

5 MODELLING AREA

The case study area is part of South and West Yorkshire, UK (see **Figure 5-1**). The definition of the case study area within South and West Yorkshire takes account of the work on Functional Areas and Regions which MVA Consultancy and David Simmonds Consultancy Ltd carried out for DfT (MVA and DSC, 2005).

More exactly, the areas are:

- 1: Bradford and Craven;
- 2: Calderdale and Kirklees;
- 3: Leeds and Wakefield;
- 4: Barnsley, Rotherham, Sheffield, and North East Derbyshire;
- 5: Doncaster and Bassetlaw.

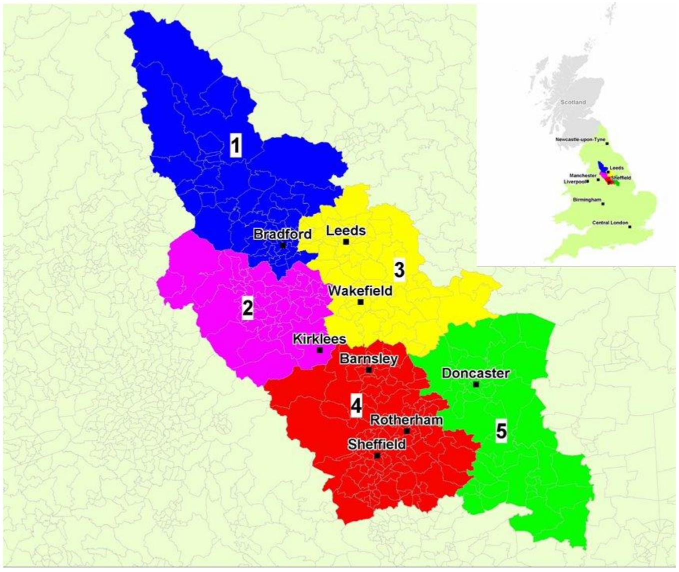

Figure 5-1 Modelling Area

6 THE STATIC SPATIAL MICROSIMULATION MODELLING METHODOLOGY

The first task in this modelling project was to construct small area population microdata at the electoral ward level on the basis of the 1991 Census Small Area Statistics (SAS) and the Samples of Anonymised Records (SARs). This involved combining a sub-set of the SARs with ward-level from the SAS to generate small area household microdata at the electoral ward level in the Yorkshire and the Humber and East Midlands, that comprise the project’s study region.

We use a combinatorial optimisation method called simulated annealing. This procedure has been used in other static spatial microsimulation applications (Ballas, 2001; Ballas et al., 2004; Williamson et al., 1998). The origin of the simulated annealing method is in thermodynamics and dates back to the 1950s, when Metropolis et al. (1953) suggested an algorithm for the efficient simulation of the evolution of a solid material to thermal equilibrium. Annealing is a physical process in which a solid material is first melted in a heat bath and then it is cooled down slowly until it crystallises. The use of simulated annealing as an optimisation method was suggested in the early 1980s, when Kirkpatrick et al. (1983) discovered an analogy between minimising the cost function of a combinatorial optimisation problem and the slow cooling of a solid until it reaches its low energy ground state. Since then, simulated annealing has been employed as an optimisation technique to solve a variety of combinatorial optimisation problems (Dowsland, 1993, Laarhoven and Aarts, 1987). In geography, simulated annealing has been applied in various contexts for different problems (Openshaw and Rao, 1995, Openshaw and Schmidt, 1996, Ballas et al., 1999, Williamson et al, 1998, Alvanides, 2000).

In the context of this project, the simulated annealing modelling code in Java adopted by SimLeeds (Ballas, 2001) has been fine-tuned used and improved in order to estimate spatially disaggregated microdata for the study region electoral wards, using data from the 1991 SARs and SAS tables from the 1991 UK Census of Population. The simulated annealing method was used to select the set of households selected (with repetition) from the records of the SARs sub-set for Yorkshire and the Humber and East Midlands, that best fits small area constraints.

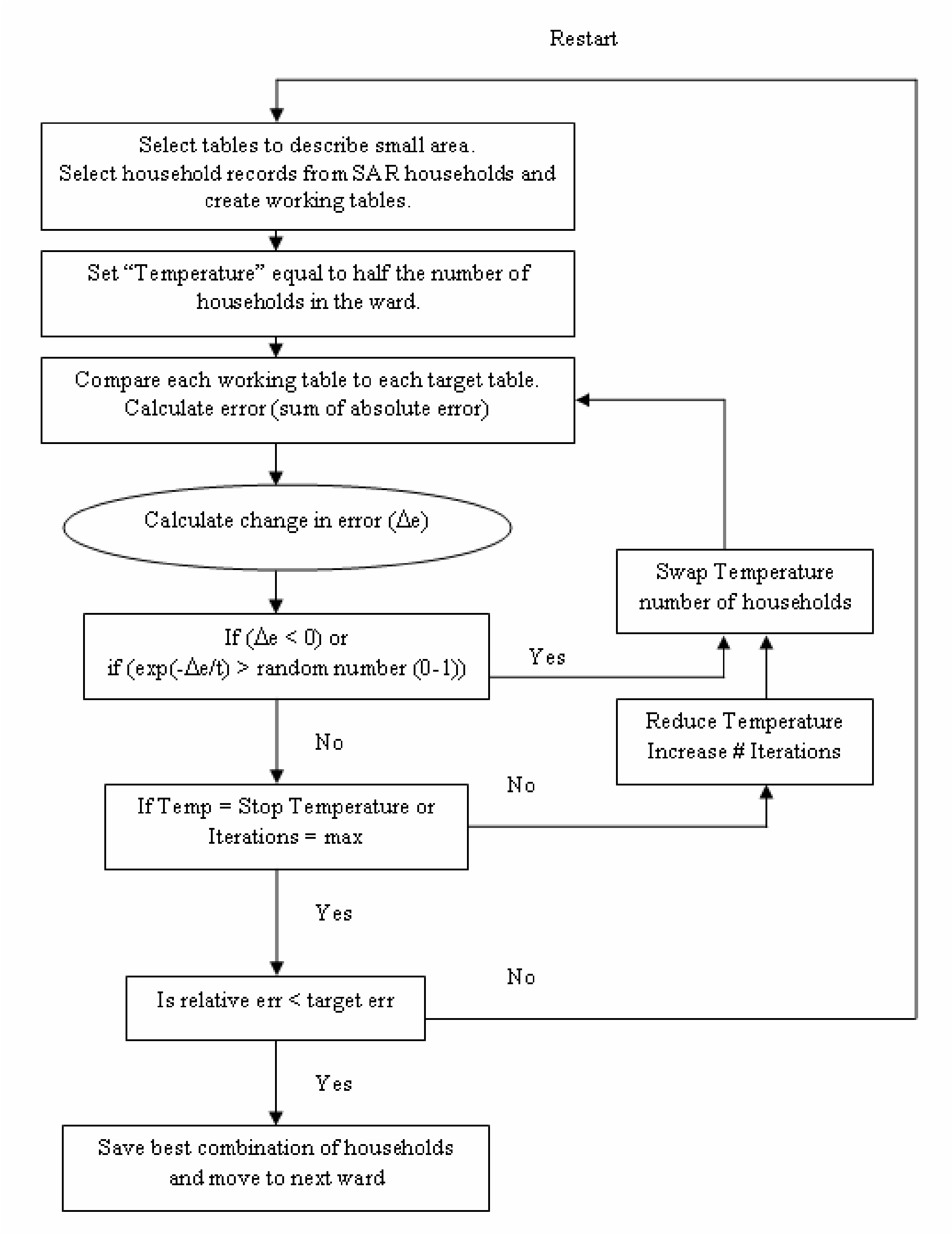

Figure 6-1 Static simulation flowchart

The simulated annealing procedure in a population spatial microsimulation context works by reading in SAS tables and SARs data, selecting SAR households at random to population the SAS tables, applying a simulated annealing algorithm to find the best fitting set of households and saving the set of SARs households that best fits the SAS tables. In particular, the algorithm works by selecting an initial random sample of records until sufficient households are represented.

Each pair of tables (simulated versus actual data) is then compared to calculate the total absolute error between the two tables. A number of records in the set are then selected at random and replaced with ones chosen at random from the universe of records. The error is then recalculated and the change in error (Δe) is calculated. If Δe is less than zero then there has been an improvement and the changes are accepted. Simulated annealing also allows sub optimal changes to occur. If Δe is positive, $\exp(-\Delta e/T)$ is compared to a random number between 0 and 1. If it is greater than the random number, then the changes are accepted, otherwise the changes are rejected and reversed. In this implementation if Δe is zero the change is accepted to allow the exploration of a greater part of the solution space. If the new error is the lowest seen so far then that set of households is stored.

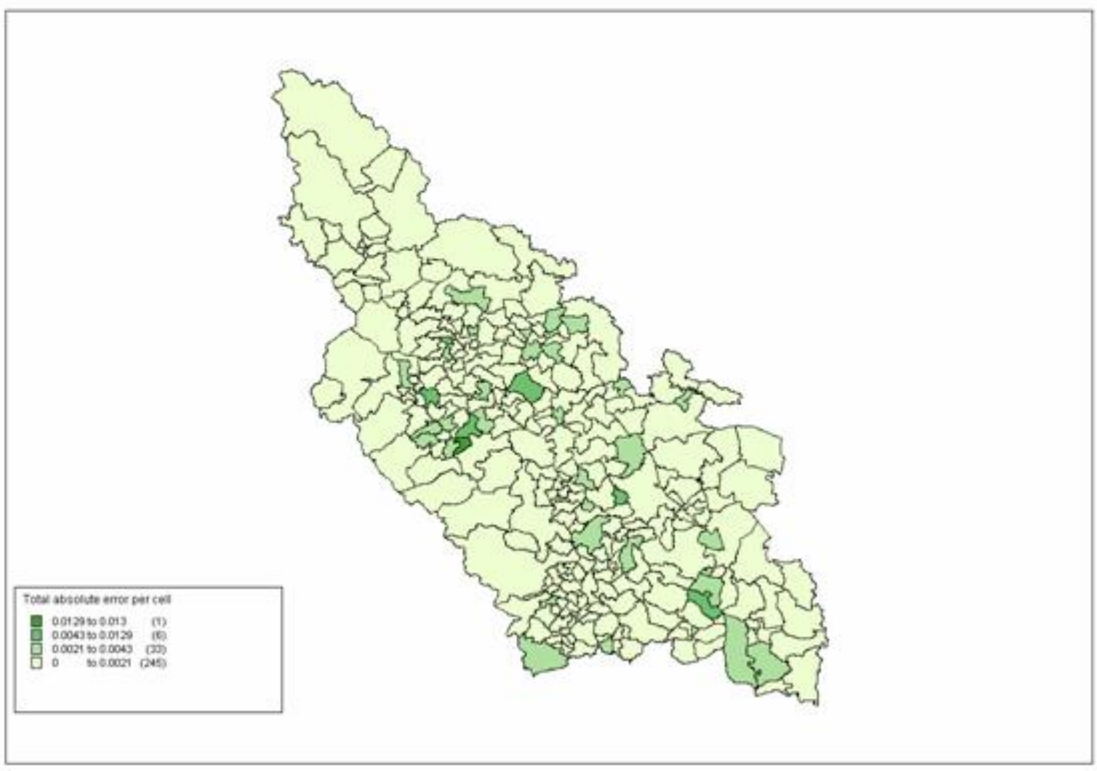

Figure 6-2 Spatial distribution of total absolute error per SAS table cell by ward

As the simulation progresses, the number of records selected for swapping at one time decreases. This process allows faster change early in the process which achieves faster improvement in the error term than selecting one record at a time, whilst progressing more slowly once the fit has improved significantly. The static model also employs a restart method which is applied if the model fails to find a satisfactory solution within the maximum permitted iterations. When a restart occurs, the simulated annealing process begins again with a new initial sample of records. The restart is used so that more household combinations can be explored. The simulation is complete when the total relative error is less than a specified target. The procedure is summarised in Figure 6-1.

The process works as an analogy with the physical process of annealing that was described above. The temperature is a control parameter and is initially set high and then slowly lowered after a set number of iterations have taken place. In the context of modelling procedure described here the initial temperature was set at 30,000 and the number of iterations at 5,000. It should be noted that the number of iterations is inversely proportional to the temperature, so that as the number of households per swap is reduced the number of iterations is increased. As the temperature is lowered fewer uphill moves are accepted because the value of $\exp(-\Delta e/T)$ is a negative function of T. The process of accepting all positive changes and some negative changes reduces the likelihood of the algorithm becoming stuck in a local minimum of error and allows a greater part of the space of possible solutions to be explored. Like the process of accepting changes that both lower and raise the error term, the restart process allows for a greater exploration of the solution space.

Figure 6-2 depicts the spatial distribution of average error (total error divided by the total number of cells that were used as constraints).

7 DYNAMIC MODEL IMPLEMENTATION

The output of the static microsimulation model provides the input for the dynamic microsimulation model as described in Section 3 of this paper, which in turn will be embedded within the aggregate DELTA and transport models to represent changes other than those in households and population. At present the dynamic microsimulation model projects the static population forward through time by simulating the processes of aging, mortality and survival, fertility, migration, couple formation and separation; the processes of household location and employment choice are currently being added.

The intention is to run the model from 1991 to 2001 and to compare the results with observed changes. It should be noted that due to the ward boundary changes between 1991 and 2001 and given that the model projects 1991 ward populations into 2001, it is not possible to use 2001 ward level Census data for validation purposes. In order to overcome this difficulty, we aggregated the 2001 Census and projected data to Local Authority level. Table 7-1 presents the actual and projected numbers of individuals for all the major Local Authorities within our study region.

As another example of the results obtained, Figure 7-1 shows the typical ward distribution of the results of the marriage generation process at local authority level. A binary logit model was used to determine whether a person wishes to marry during the current time period, using Monte Carlo Simulation, as a function of age and marital status. This was only applied to one gender, to avoid double counting. The person searched the population to find an unmarried member of the opposite gender within the appropriate age range, which was defined using data from the Census. If no suitable partner could be found the person searching stayed in the same marital status as previously.

Table 7-1: Actual and Projected numbers of individuals, 1991-2001

Local authority	Actual 1991	Projected 2001	Actual 2001	Difference (projected-observed)	Projected. rate of change	Actual rate of change	Difference (projected - actual)
Barnsley	218,556	220,338	218,070	2,268	0.8%	-0.2%	1.0%
Doncaster	285,022	288,722	286,863	1,859	1.3%	0.6%	0.7%
Rotherham	249,692	253,685	248,174	5,511	1.6%	-0.6%	2.2%
Sheffield	496,215	490,320	513,235	-22,915	-1.2%	3.4%	-4.6%
Bradford	451,050	460,008	467,664	-7,656	1.9%	3.7%	-1.7%
Calderdale	189,444	190,315	192,401	-2,086	0.5%	1.6%	-1.1%
Kirklees	369,534	374,406	388,555	-14,149	1.3%	5.1%	-3.8%
Leeds	648,572	651,237	688,938	-37,701	0.4%	6.2%	-5.8%
Wakefield	307,765	313,410	315,173	-1,763	1.8%	2.4%	-0.6%
North East Derbyshire	46,397	46,650	45,815	835	0.5%	-1.3%	1.8%
Bassetlaw	98,779	99,290	100,921	-1,631	0.5%	2.2%	-1.7%
Total/Average	**3,388,381**	**3,440,468**	**3,465,809**	**-77,428**	**1.5%**	**2.3%**	**-0.8%**

The process is a simple application of conditional probabilities (i.e. a non-choice process followed by a search) but will be developed

- to take account of all couple formations, ie all people who are intending to live together as a couple (and who can be assumed to seek a dwelling as a couple);
- to identify the proportion of these who marry (and who may marry long after forming a couple);
- so that partners are generally found within the area of residence rather than throughout the full system;
- to allow for migration by people by people who do form couples with persons from other regions;
- to allow for the formation of “potential couples”, i.e. those persons who will not actually live together (with or without marrying) until they find suitable housing.

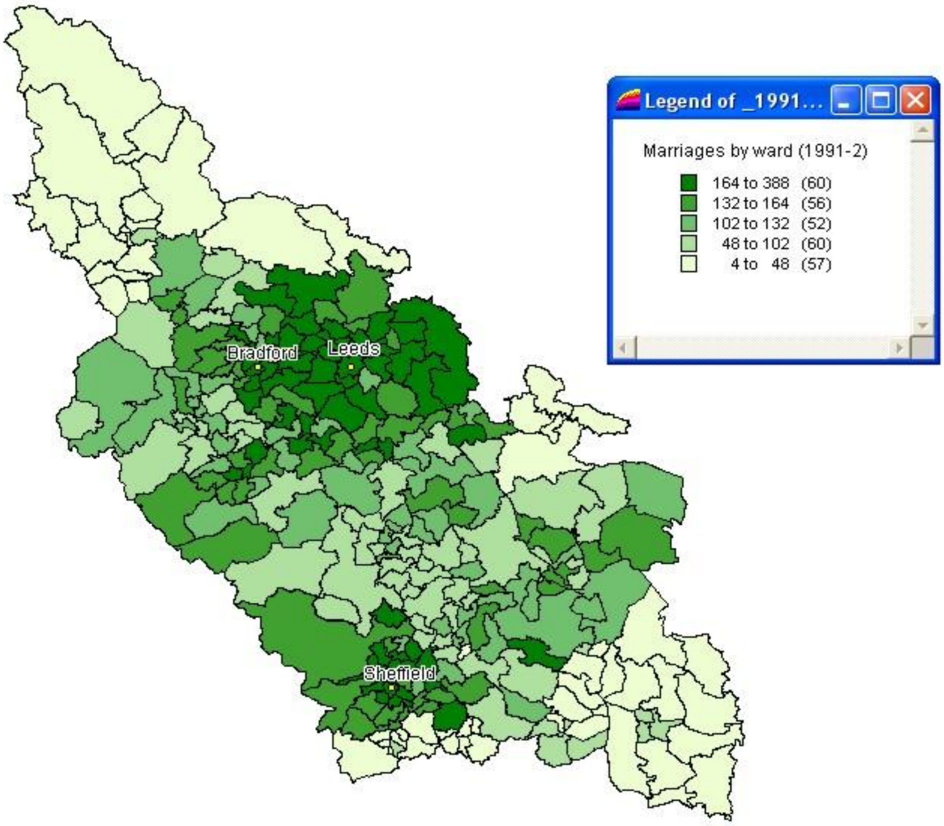

Figure 7-1. Marriages by ward (12 months period)

Further results should be available for presentation and discussion at CUPUM 2005.

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