

# A hybrid spatial microsimulation model for decision support in demographic planning

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## Abstract

Individual based models such as Microsimulation models (MSM) provide an alternative to macroscopic models in social simulation and modelling. In contrast to the traditional models where individual characteristics are often blurred or even disappeared, MSM provides the realistic disaggregated information that is often vital for modern policy problems. MSM has been extensively applied and well tested in social modelling. However, it has been criticised for being less strong in modelling interactions between individuals and their behaviours. MSM also struggles where realistic micro-data are not available. ABM (Agent Based Model) can model the demographic process through interactions between the agents and with the environment that they live in. The combination of MSM and ABM provides us a new approach to enhance complex social modelling. In *Moses*, we attempt to provide better groundwork to facilitate the policy and decision making for the UK population through a hybrid model that combines the strength of the two complementary techniques.

## 1 Introduction

New tools in the history of science often launch new ways of looking at the world. The computer has now become a tool poised to reshape our thinking in many fields. Computer based social models and simulations now play an increasingly important role in understanding social systems. Such simulation models can trace the evolution of the modelled system over time. Combining data from past trends with assumptions about the key relationships among relevant factors, this provides the basis to study phenomena such as the interactions of a social system with policy and can therefore lead to valuable practical applications as decision support systems and pedagogic tools to understand how a social system works.

Modern policy problems often demand realistic disaggregated information of the individuals. Thus individual based models such as Microsimulation models (MSM) provide an alternative to traditional macroscopic models. Large-scale MSM can provide the response variability of the model system to the same/similar level as the real system in order to study the effects of policy changes. As geography has a known important impact on individual behaviours, spatial MSM can accommodate such

policy requirement and simulate virtual populations in given geographical areas, taking the local contexts into consideration.

MSM is a used and tested technique in social modelling and its strength has been demonstrated in many previous studies. However, MSM requires realistic micro-data and will struggle in occasions where such data are not available. In a population MSM, the probability driven processes makes it less flexible in modelling interactions and behaviours of various population groups. ABM (Agent Based Models) can strengthen the interaction and behaviour modelling by modelling the demographic process through interactions with other agents/ the environment that they live in and actions according to their unique built-in rule of behaviours. The flexibility of construction of heterogeneous agents and their rules makes it particularly helpful when there is a knowledge gap/unavailability of data.

Moses (Modelling and Simulation for e-Social Science) is a dynamic spatial MSM that simulates discrete demographic processes at a fine spatial scale and project the individuals into the future from year 2001 to 2031. Moses was also the name of a research node of the national e-social science centre of UK. This paper describes the hybrid approach used in Moses that combines the strengths of both MSM and ABM to enable the modelling of complex social systems. The results generated by the model and our attempts to various experiments with different sub-populations will also be discussed in this paper.

## **2 Background**

Microsimulation Models (MSM) were first constructed in the 1950s by Orcutt (1957) working in the USA and by Hagerstrand (1957) working in Sweden. Orcutt and colleagues developed DYNASIM as an MSM for individuals as decision-making units in order to understand the impacts of new public policies, eg. taxation and benefit (Orcutt et al., 1986). Hagerstrand's work on migration of individuals in central Sweden incorporated space into MSM and used a mixture of empirical "information fields" and decision rules to model inter-zonal migration. From these economic and geographical roots, MSM have spread across the whole social science spectrum. It has now become a pre-eminent type of social model (Brown and Harding, 2002). Major micorsimulation model developments have been seen around the world during the past few decades. Such developments include: CORSIM (Caldwell 1993) in the United States, DYNACAN (Morrison, 2003) in Canada, SVERIGE in Sweden (Rephann, 1999), PENSIM in UK (Curry, 1995), APPSIM in Australia (Harding, 2007) and on the scale of the whole Europe, EUROMOD (Sutherland, 2007).

Today the increasing availability of large and detailed datasets on individuals, developments in computing power and analytical techniques allow a greater sophistication for MSM to attempt to model large complex social systems. In order to study the real effects of policy changes, a good level of heterogeneity of the individual decision units is needed. Population size, both in terms of actors and their inter-relations and interactions, is often important for such systems. Bigger groups create additional dynamics and consequently the levels of variability and stochasticity within the simulation model will change. Therefore a large scale model can help to account for unforeseen effects that are not modelled explicitly. Such features have

been demonstrated in many national or multi-national MSMs, including those introduced above.

Dynamic MSM feature more detailed and realistic population ageing than static MSM. There is general acceptance that dynamic models provide a more realistic representation of micro population unit behaviour. As we all live in a local area and are affected by what happens around us, geography plays an indispensable role in influencing social progress and welfare. Therefore it is important for local characteristics and interactions to be modelled in order to understand the whole picture of a social system. Such local context can also demonstrate various individual characteristics to a degree. A spatial MSM simulates virtual populations in given geographical areas so that local contexts can be taken into account when studying the characteristics of these populations.

The Moses MSM models UK individuals and households in the form of a dynamic spatial MSM, which draws on rich attributes of individuals and households from a diverse portfolio of databases and to provide a generic framework for social scientists and decision makers with a shared interest in modelling and simulation of social systems within an urban environment. In the following sections, the modelling method, model structure and results of the Moses MSM will be discussed in more details.

### **3 The Moses dynamic spatial MSM**

As the richness in an MSM can serve as a device for the representation of both relationships between members of a population, and of the transitions between states within a population (van Imhoff and Post, 1998), Moses uses an MSM for the population and its dynamics, but the model structure parallels the macro multi-state cohort-component (MSCC) projection model. Individuals are annually projected by gender and single year of age at the level of ward. The population at the end of the year is equal to the population at the beginning of the year plus natural change and net migration. The model projects each component of population change (births, deaths, household formation, health change and migration) separately, but each component of change affects the others. For instance, a large number of young female migrants moving into one area will increase the local births significantly.

The Moses simulation is based on a synthetic population generated through reweighting the 2001 UK census data to individual census wards, using the Household Sample of Anonymised Records (HSAR). HSAR comprises a 1% sample of households from the UK Census of 2001 in which the census questionnaires are completely enumerated for households and their constituent individuals. BHPS has also been used for extra information on lifestyles, attitudes, and household income and expenditure profiles. The longitudinal study of BHPS also provides a view of household change through time, from 1991 up until the present day. In this study, the HSAR is used as the raw material for the population reconstruction model, while BHPS is used extensively in the extraction of relationships for the dynamic model (Birkin and Wu, 2008).

### 3.1 System components

Moses aims to provide a dynamic representation of key demographic events/transactions in a geographically identified population. There are six important demographic processes modelled in Moses: Ageing, Mortality, Fertility, Health change, Household formation and Migration. The ageing process is straightforward and each surviving individual simply ages one more year at the end of each step of the simulation. The rest of main system components are described below:

- **Mortality:** The mortality component of the dynamic model predicts the expected number of deaths within each UK census ward, using data obtained from census data and vital statistics data from the Office of National Statistics (ONS). At each time period, a survival probability is applied to each individual on the basis of age, gender and location.
- **Fertility:** Ward-specific fertility rates are derived in a rather similar way to the mortality rates, with national rates again being localized in accordance with ONS Vital Statistics.
- **Health:** Individual health states are recorded in the HSAR and SAS using three categories which are “Good”, “Fairly Good” and “Not Good”, which are used within the simulation. For each individual, the probability of a change in health status is assumed to be dependent on current health status, age and gender.
- **Household formation:** Changes in household composition are determined by four processes in the model. These are the formation of new unions (including marriage), the dissolution of existing unions, movements in which one or more persons leave a household and the death of a household member.
- **Migration:** In order to accommodate migration, the model has two important features: a stock of houses that are independent from the households that occupy them, and a location search process that is mediated through an aggregate spatial interaction model of migration. This model recognises different households according to their size, composition and age, different housing preferences and search horizons.

As an individual based UK population model with rich attributes, Moses has to face a series of challenges. In the section below, we will discuss the main challenges for Moses. For illustrative purposes we use an example of the application of the model to the urban area of Leeds, a city of 750,000 people in the north of England throughout this paper, but the MSMS is generalisable between local areas across the United Kingdom.

### 3.2 Main Challenges for Moses

There are about 61 million individuals in UK (761 thousand in Leeds) (mid-2007) that need to be modelled in Moses. So dealing with such scale is the first challenge. However, the scale challenge for Moses arises not only from the size of the base

population we are modelling, but also from the richness of the attributes, probability generation and updating.

HSAR comprises a portfolio of more than 50 characteristics for every individual in a household, ranging from social and demographic variables to property type, employment and education (CCSR, 2005). As a spatial dynamic MSM, Moses models individuals in small areas of wards, where extra local area information is required. For instance, the total number of people, the total number of households, the total housing units in the area (to facilitate the migration process) and the information about the area itself. As individuals are modelled as members of households, some relationship information is also stored that is useful for various policy applications, such as those concerned with babies and their mothers, child dependents, elderly dependents and many more.

All MSM have to go through the non-trivial process of probability generation and updating. To capture the detailed characteristic of the local population, Moses uses not only age and sex specific probabilities, but also attempts to estimate values as close as possible to the modelled population in reality. That is, the probabilities are estimated at the smallest reasonable scale and then used with a random number to determine whether an individual survives or dies. Take Leeds for example, survival rates in the model are derived separately for each of 33 census wards, both genders, and 101 individual age groups, giving a total of 6,666 individual parameters. Age and gender specific rates are derived from national data (for the year 2001) in which the number of deaths for each group can be normalised by age-specific populations at risk. These national rates are then applied to the population-at-risk within each census ward in the Leeds area to yield the expected number of deaths. This prediction is compared to known death totals for each ward from ONS Vital Statistics (again for base year 2001) and an appropriate multiplier is applied within each ward in order to balance observed and predicted deaths. In each time period, a survival probability is applied to each individual on the basis of age, gender and location. The model is run in annual time increments. The ageing rule for all survivors is that they become a single year older in each time step.

It can be seen that for this part of the model alone, projection of mortality over a 30 year time interval involves the estimation of roughly 200,000 individual mortality rates. In order to make this problem manageable, Moses has adopted a fixed percentage reduction in mortality rates for 22 (instead of 202) age-gender groups and location combinations at each time step in the simulation. Mortality is a pretty straightforward process, for each individual, only one probability is required. However, when tackling more complex processes, multiple probability generation and updating are required for multiple stage modelling. For instance, in migration process, we need to find out who is to move, whether they move as individuals or households and where to move to.

It is also worth keeping in mind that when simulating events, there will be a need to simulate the following consequences. For instance, moving an individual from current position to another will lead to a series of updates after each event. In the migration example, when a Household Reference Person (HRP) moves out, it is necessary to choose a new HRP, update each individual statuses, update household attributes, update area attributes. Similar simulations are necessary at the new destination the

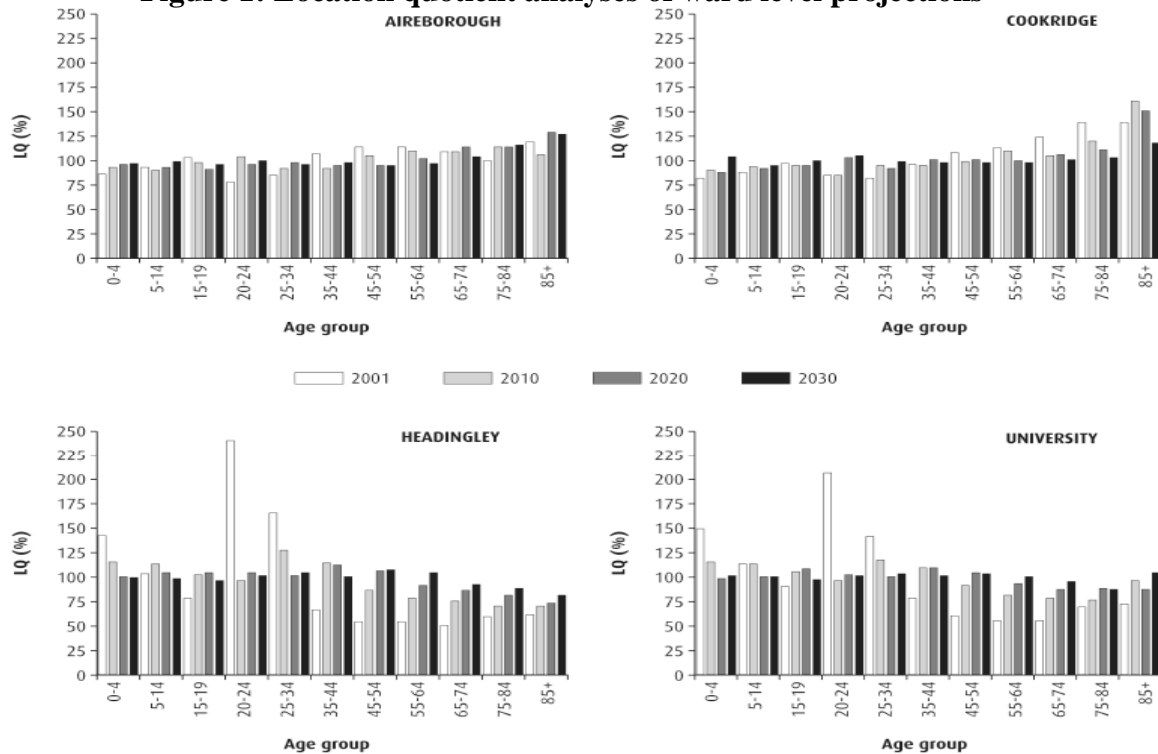
previous HRP moves to. All the processing described above adds to the scale challenge and makes it very demanding in terms of computing power and skills. The application of MSM in Moses has demonstrated the strength of MSM in modelling such large complex social systems.

Another challenge arises from Moses' attempt to model the movement, interaction and behaviour of the individuals within the system. After all, moving around is the next important change in a population after the matter of life and death. For planning purpose, the interactions and behaviours among the individual decision making units in a social system play a vital role. MSM rely on good micro-data to be able to produce reasonable results for each of the phenomena. However, there is a struggle between the quality of the micro-data and reasonable results in MSM. Moses attempts to strengthen the model on aspects of the interaction and behaviour modelling and bridge the gap between the available data and decision making by adopting a hybrid modelling approach, where SIM and ABM are introduced into the MSM.

### 3.3 Limitations of the Moses MSM

Moses attempts to provide support for decision making at both strategic and tactic level. The initial results have been analysed and the MSM representation looks reasonable at the city level. This is very useful in assisting strategic decision making. More details of the results are described in Birkin et al. (2009). In this paper we will focus on the limitations of model on the small area level. When location quotients are used to assess the population profile in wards, limitations of the model has been found in some small areas. In suburban areas such as Aireborough and Cookridge, the ageing over time looks plausible. However, in wards where student migration has a great impact on local population structure such as University and Headingley, the MSM failed to reproduce the student population renewal. The distinctive pattern of the large volume of student migration into and out of the "student" wards each year has disappeared. As a result, the ageing trend of population in these areas has been greatly exaggerated. This indicates that the subtlety of the local migration behaviours has not been captured successfully by MSM (Figure 1). The following section will describe how Moses attempts to address this issue through a hybrid model.

**Figure 1: Location quotient analyses of ward level projections**



Source: Computed by the authors using 2001 Census statistics and simulated populations

#### 4 The hybrid model of Moses

Moses exploits the well-known strength of MSM for list processing based on well-defined rules. Ageing, fertility and mortality can all be simulated easily by this means. However, once we start to introduce concepts of movement and interaction, then the standard MSM process begins to struggle. We then combined the MSM with a Spatial Interaction Model (SIM) to improve the migration projection. The results have substantially improved for migration at the meso level. Forecasting the behaviour of the student migrants at the small area level still proves to be difficult using an SIM approach, due to the distinctive migration pattern of this sub-population (Wu et al., 2008). Despite its many strengths and advantages, we argue that a MSM of a spatially distributed population depends on good data about the important transitions which are experienced by individuals. Because of this dependency, MSM is less strong in modelling individual behaviours where realistic micro-data are unavailable. The structure of MSM is also found less flexible to accommodate various rules for different individuals. An ABM can be introduced into the MSM to strengthen such aspects of the model.

It is generally recognised that agents are an effective way to represent individual entities that move around and interact with one another and with their environment based on built-in rules (Billari et al., 2002). Such rules can be very simple and flexible at the individual level, but the simulation through a large number of agents can reproduce complex social phenomena at the macroscopic level, with leverage for unexpected patterns that are not intentionally modelled in the rules. Such a property makes it possible for an ABM to reflect the characteristics of a society more

realistically and makes it a technique complementary to MSM in modelling a complex social system. Mobile agents in an ABM interacting with an environment and other agents look like an ideal partner to static, self-contained individuals in an MSM, especially in more complex demographic processes such as migration, where interactions and behaviours play an important role. In his famous study of residential segregation, Schelling's (1971) analysis posits a relationship between individual decisions to move and the composition of neighbourhoods. This process can easily be represented within an agent based migration model. Therefore an agent-based mechanism can be used in this way to help maintain geodemographic discrimination within urban population projections.

In this paper we investigate the usefulness of a hybrid modelling approach in a series of experiments where the MSM is combined with ABM to allow flexibility to explore evolutions of demographic structures in various scenarios.

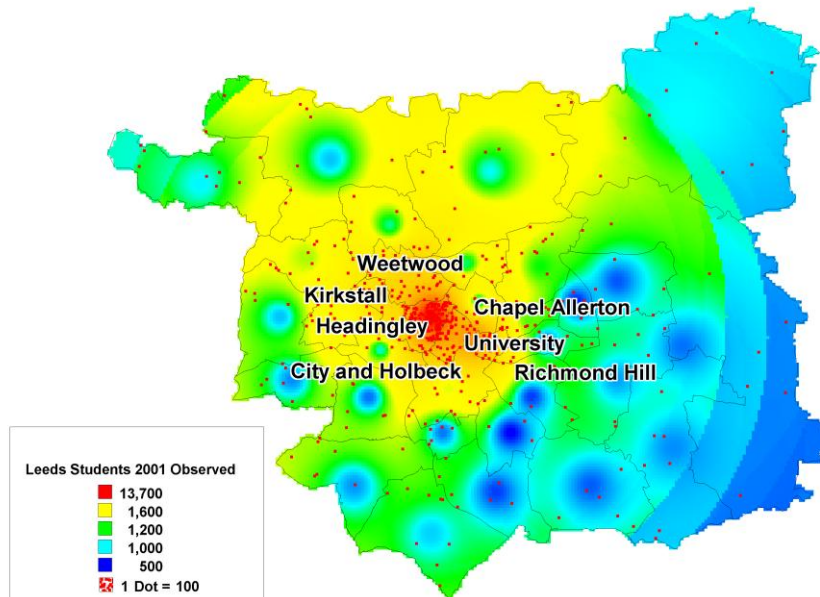
#### **4.1 ABM experiment: student migration**

Due to its distinctive migration patterns and lack of information on student migrants, the problem of modelling student migration is quite well-known in small area demographic modelling (Baryla & Dotterweich, 2001; Fotheringham et al., 2004; Koser & Salt, 1997; Rees, 1994). Frequent movement in small areas during their period of university study, their attitude towards census and large surveys and the confusion of the definition of term-time and home address all make the production of useful student migration micro-data difficult. We know that university students tend to only stay in certain areas, mostly around the universities they study, during the period of their study. Most of them then leave while other new students move in, instead of growing old with the rest of population in the area. Due to the replenishment of the student population each year, the population in such wards stays younger than that in other wards. As an ABM is very flexible in terms of constructing heterogeneous agents with different built in rules, we experiment with an ABM for the student migration process using hypothetical rules in the same way as Schelling (1971).

In Moses ABM, we recognise the four types of agents/students: first year undergraduates, year 2 and 3 undergraduates, master's students and doctoral students. Based on the above assumptions, we then apply the some general rules to the students, in terms of the areas they stay in and the duration of their stay. Specific rules for individual groups vary according to their distinctive features. For example, a year two undergraduate student can stay in the area for two years. They can then have the chance to continue studying towards a master's degree for one more year or leave. While a master's students can stay in the area for one year and then continue with a doctoral study for three more years or leave the area. The typical interaction between the agents/students themselves would be to look for the fellow students in order to move to the area they stay in and the interaction with the environment would be checking if there is a vacancy in that area. An agent/student keeps searching in areas where their fellow students live until they find a vacancy to move in. The agent without success at the end of the search stays in the current area.

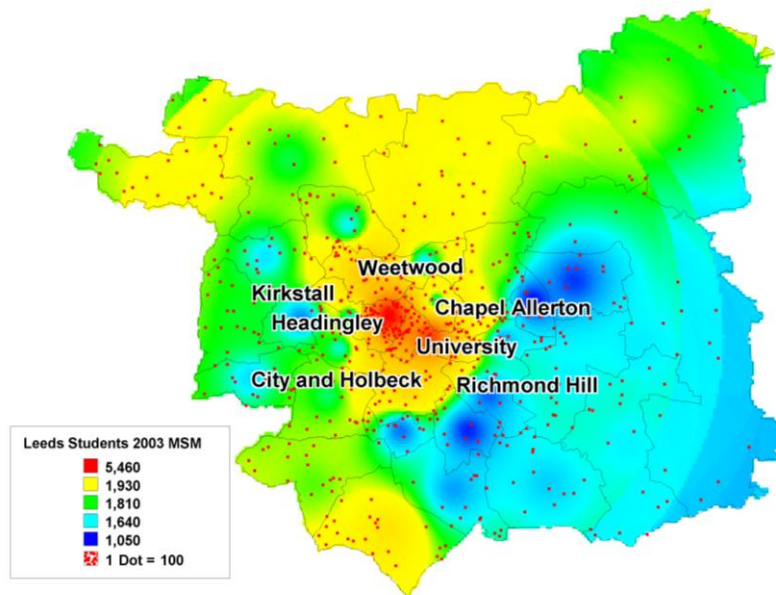
The simulation results of the student population using the pure MSM and using the hybrid model have been compared to the observed distribution of the student population. Instead of students almost evenly scattering around the whole city in the MSM, the hybrid model provides a much better reflection of the observed student population concentration around the city centre, close to the universities. Most students will leave upon completion of their study in the hybrid model as new students come into the area each year. In other words, students are no longer growing old together with the rest of the population in the suburban areas as simulated in pure MSM. The distribution patterns of the student population within Leeds city can be observed clearly in the maps below (Figure 2, 3 and 4). A full comparison can be found in Wu et al. (2008).

**Figure 2. Leeds students: observed**



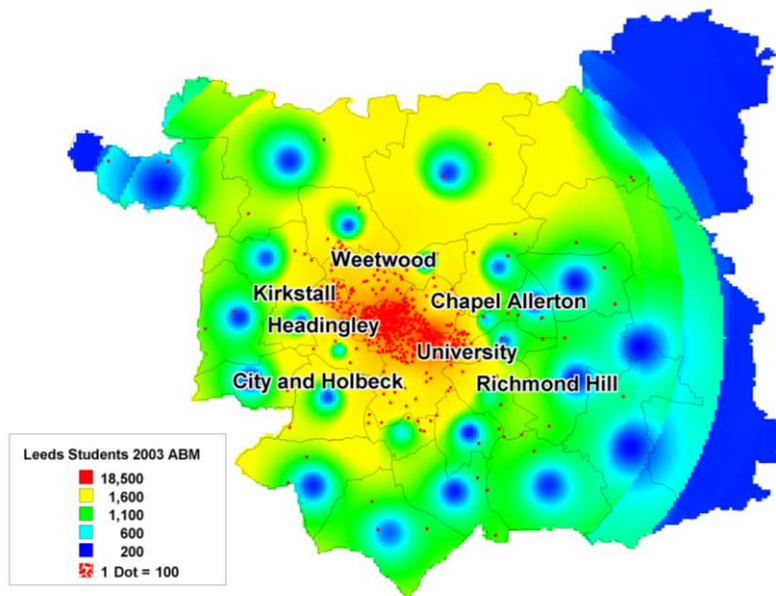
Source: Generated by the authors using 2001 Census statistics and ward boundaries.  
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**Figure 3. Leeds students: pure MSM result**



Source: Authors' computations; Ward Boundaries. Crown copyright 2003.

**Figure 4. Leeds students: hybrid model result**



Source: Authors' computations; Ward Boundaries. Crown copyright 2003.

## 4.2 ABM experiment: the impact of personal history on mortality

One of the advantages with simulating geographically identified populations is that the local context can demonstrate the individual characteristics to a degree. However, sometimes it is not only the current small area that influences behaviour but the places individuals came from or used to live in often also play an important role. In some demographic processes such history can have a great impact. One simple example can be: if a person has worked as a miner all his life, his/her mortality/morbidity rates should not suddenly change a great deal just because he/she retired to a pleasant residential area. In order to model such impacts, we need assess each individual's behaviour using information from their personal history. An ABM can meet such requirements with much more ease than an MSM, as agents can simply have a function to retrieve specified information from their own history that they carried along. Based on the hypothesis that mortality/morbidity probabilities depend on not only on the current personal and environmental conditions of the individual, but also depend on their personal histories, we explored 3 scenarios of mortality projections in Moses hybrid model.

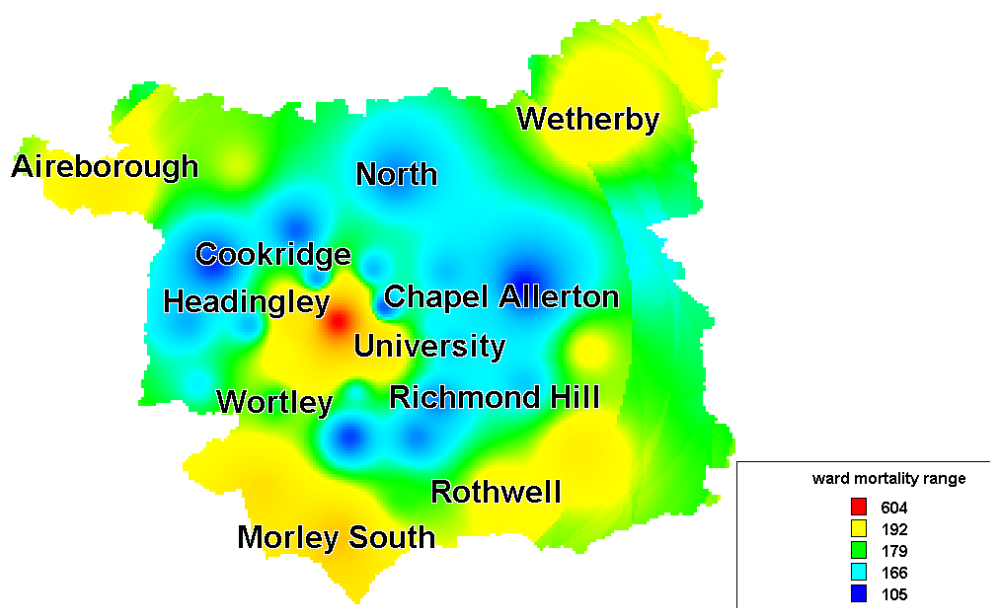
In this experiment, three scenarios were specified: (1) mortality projected on the basis of current destinations, (2) mortality dependent on origins/birth places and (3) mortality dependent on personal migration histories. For simplicity, this experiment has been restricted to the wards within Leeds. In the 1<sup>st</sup> scenario, all individuals are simulated using a MSM. Their survivals are determined against an age, sex and location specific mortality probability generated on the basis of local information about the current location of residence. A hybrid approach is used in the 2<sup>nd</sup> and 3<sup>rd</sup> scenarios, where agents carry their own histories along with them and have the ability to check on such histories. In the 2<sup>nd</sup> scenario, the survivals are determined on the basis of the mortality rates of individual origins/birth places. In the 3<sup>rd</sup> scenario, we tried to model the impact of personal migration history on mortality. Mortality is projected on the basis of the mortality rates of the area where the individual stays the longest to date. Take a simple example of an individual migrant in Leeds, who we can call migrant A here. If his origin is ward 1 and in the last 5 years his migration destinations are: ward 2 in year 1, ward 2 in year 2, ward 2 in year 3, ward 3 in year 4, ward 4 in year 5. Then in the 1<sup>st</sup> scenario, migrant A will check his current location and decides that his mortality probability in year 6 will be determined against the age-sex specific probability in ward 4 that corresponding to his age-sex group, while in the 2<sup>nd</sup> scenario, his mortality probability will be based on his age-sex specific probability in his origin: ward 1 and in the 3<sup>rd</sup> scenario, his mortality probability will be based on his age-sex specific probability in the area that he stayed the longest, ward 2. Such changes in the individuals, both different types of migrants and non-migrants, can be interesting for various researches and will result significant changes in local population structure.

In the experiments, the whole population of Leeds has been simulated under the three assumptions for 30 years and the results of year 2031 are then compared spatially to assess the difference in the mortality distribution within the city. Although the distribution pattern of mortality is similar on the whole, the experiments also reveal some interesting variations in small areas. Unsurprisingly, the mortality projection based on origins is more different from the 1<sup>st</sup> scenario, the projection based on current locations. While the projection based on individual migration history demonstrate

more similarity with the 1<sup>st</sup> scenario. From the map below, we can see that higher mortality has spread into the suburban areas in the 2<sup>nd</sup> scenario, especially in the areas between Aireborough and North. The southeast area also suggests significant increase of mortality. While the 3<sup>rd</sup> scenario indicates a reduction of mortality in the belt immediately around the high mortality risk area in the city centre. The southeast area however suggests more increase of mortality even than in the 2<sup>nd</sup> scenario. Such findings demonstrate that personal history does have important impact on mortality (Figure 5, 6, 7).

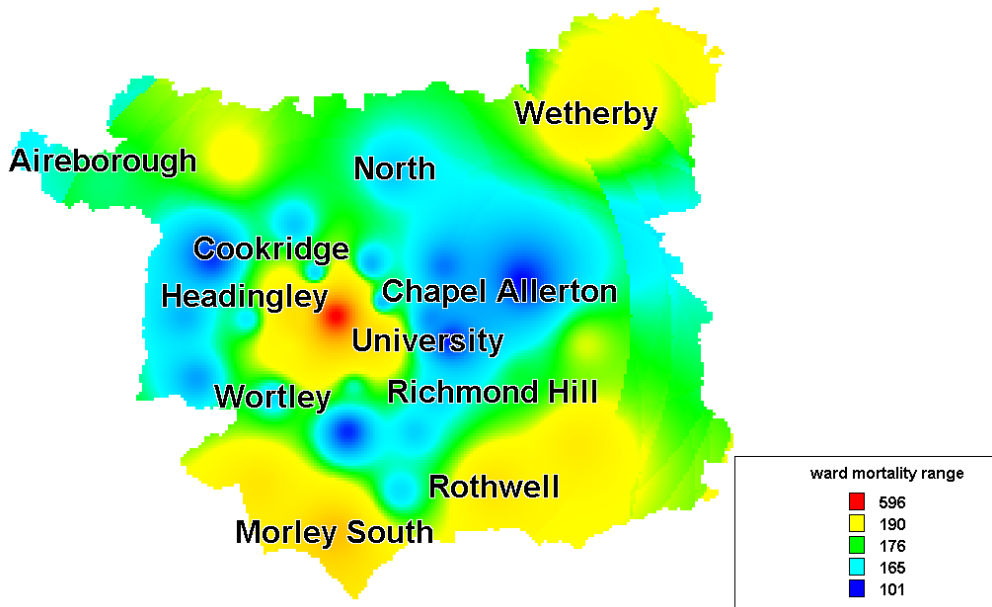
Empirical research on the relationship between limiting long-term illness and migration (Norman et al. 2004) established that the illness status of migrants is mid-way between that of their origin and destination locations. If this finding also applies to mortality, then a combination of all three scenarios may be needed to represent the mortality chances of migrant properly. We will continue improve the mortality projection in the light of such facts. Although the mortality experiments discussed here are purely based on hypothesis, it demonstrates that there are many more aspects of the population MSM can be strengthened through ABM techniques. Such explorations are not only just interesting experiments, but potentially can play a vital role in facilitating the decision making where the impact of personal history is required to be taken into account.

**Figure 5 Mortality experiment based on current location: results in year 2031**



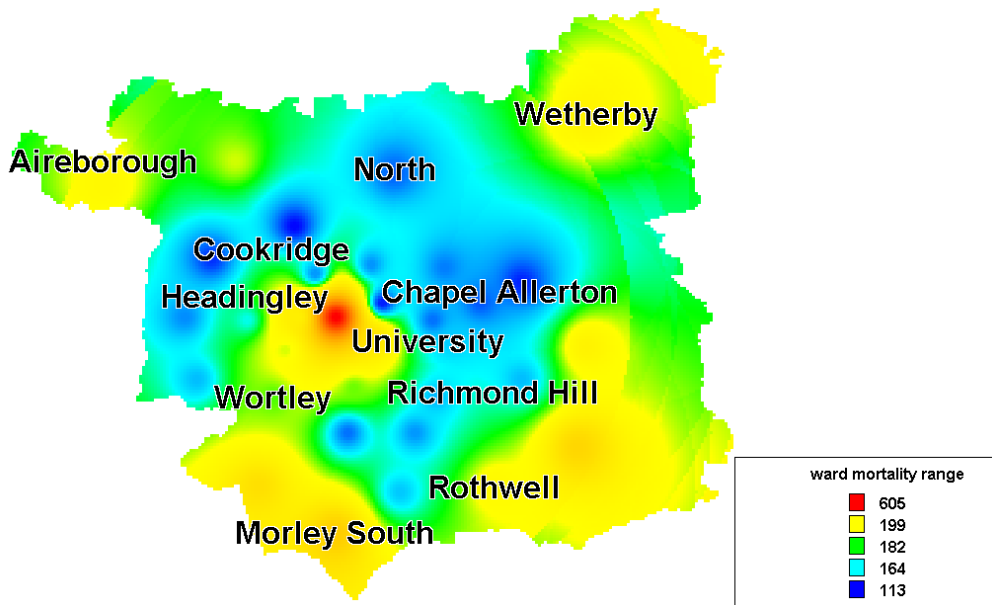
Source: Authors' computations; Ward boundaries, Crown copyright 2003.

**Figure 6 Mortality experiment based on origins: results in year 2031**



Source: Authors' computations; Ward Boundaries. Crown copyright 2003.

**Figure 7 Mortality experiment based on migration history: results in year 2031**



Source: Authors' computations; Ward Boundaries. Crown copyright 2003.

## 5 Conclusions

In this paper, we introduced a spatial dynamic MSM, Moses. The structure and method used in the model have been described. Detailed results analyses are described in Birkin et al. (2009). Moses has faced the challenges of modelling large complex social system in a fine geographical scale and attempts to capture the distinctive patterns of movement, interaction and behaviours of various sub-populations. Through the efforts on improving the model results at the finer level of spatial scales, we have built an ambitious hybrid model which combines MSM, SIM and ABM features. Adopting the hybrid approach, we have achieved the goal of both the effective handling of large scale individual based system and extra flexibility to model various behaviours of sub-populations in different scenarios.

In the examples we described above, we deliberately chose the most straightforward processes and applied ABM with considerable simplification. However, the modelling of interaction, behaviour and personal history impact can be significantly more complex with intelligent agents. For example, people can have much more complex interactions with others and their environment to make a decision or take an action based on their personal history or requirement during the Household formation process. The examples discussed in this paper are simply used to demonstrate the potentials of the hybrid model.

As a demographic planning tool, Moses can monitor the evolution of population structures and various demographic change patterns on a fine geographical scale. This provides the vital information for demographic planning/policy making. Moses can also benefit other public policy making or public service planning. For instance, the ageing trends in certain suburban areas may promote changes in health service and public transport service provision in order to enable easy access to such services for the old and frail in the area. The rich attributes captured in the system are also very useful in various policy analyses or research purposes.

The Moses hybrid model has provided a framework to enable the effective modelling of individual decision making units on a large scale, as well as adding the flexibility to introduce different modelling techniques to strengthen various aspects of the model. The model itself provides a useful tool in assisting decision making, exploring various “what if” situations and testing different hypotheses. As we have discussed above, the hybrid modelling approach demonstrates great potential in demographic modelling and we will continue trying to improve various aspect of this model using this approach to provide a better groundwork for decision making and predicting the future.

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## GLOSSARY OF TERM

ABM	Agent Based Model
BHPS	British Household Panel Studies
HRP	Household Reference Person
HSAR	Household Sample of Anonymised Records
Moses	Modelling and Simulation for e-Social Science
MSCC	Multi-State Cohort Component model
MSM	Micro-Simulation Model
ONS	Office for National Statistics
SIM	Spatial Interaction Model

UK	United Kingdom
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