MICROSIMULATION METHODS IN SPATIAL ANALYSIS AND PLANNING

By
Martin Clarke* and Einar Holm**

ABSTRACT. Despite the significant potential afforded to model based geography by microsimulation methods they are still largely ignored by spatial analysts. In the worse case there is the possibility of the method being reinvented by different researchers independently. In this paper we attempt to describe the main features of the method and to briefly review some of the more important applications. We also speculate on some future developments of the methodology in the area of social and economic geography.

1 Introduction

The development and application of microsimulation methods in geography and planning offers considerable scope and potential for the analysis of a variety of systems and associated policy issues. In this paper we wish to describe the main principles and features of microsimulation. One motivation for attempting to do this centers on the fact that the majority of the theoretical and empirical developments in the application of microsimulation (with a few notable exceptions) have occurred in disciplines other than geography and that the significant contribution that these methods can make have largely been ignored by geographic modellers. A related problem is that there exists a danger of 'reinventing the wheel'—the advantages and problems associated with the methodology are recognised independently of the literature on the subject.

Almost 30 years ago the economist Guy Orcutt set about developing a radically different approach to modelling the U.S. economy. Traditionally this had been attempted using macro-economic approaches such as those developed by Tinbergen (1939) and Leontieff (1951). The central feature of Orcutt's approach was the identification and representation of individual actors in the economic system and the way in which their behaviour changed over time. In principle these could include individuals, households, firms, banks, corporations, and so on. This shift of focus, from sectors of the economy to the individual decision making units is the basis of all microsimulation work that has followed from Orcutt's work. At about the same time Torsten Hägerstrand proposed a micro-approach to the modelling of innovation diffusion in a spatial system. Both approaches were stimulated through a realisation that a more realistic picture of aggregate behaviour could be obtained through an analysis of underlying micro-processes as represented through the interactions of the basic decision units in the system. We shall discuss in some detail in section 2 the justification for adopting a micro-level approach particularly when we are concerned with a spatial dimension. The advantages and disadvantages of doing so are often overstated and need careful articulation. In section 2 we shall also describe how simulation of a micro-data base can be performed using a number of alternative methods and examine the main attractions and disadvantages associated with these. Additionally we discuss how geographical theory can be embedded into microsimulation models and how this relates to other on-going research. Section 3 is devoted to looking at some of the main practical and computational issues faced when implementing microsimulation models. In section 4 we review some of the main applications of the methodology, particularly those with a spatial component. We shall put forward a number of hypotheses to explain the paucity of applications in geography and regional science despite the burgeoning interest in the economic literature. Finally, in section 5, we propose a number of further extensions that appear to the authors as offering considerable potential to geographical analysis in a number of different areas.

2 Main principles and features of micro-simulation

2.1 Introduction

In this section we describe some of the background to the development of microsimulation as

* Martin Clarke, School of Geography, University of Leeds, Leeds, LS2 9JT, U.K.
** Einar Holm, Department of Geography, University of Umeå, S-901 87 Umeå, Sweden

a tool for analysis in socio-economic systems. There are a number of different issues that can be identified as warranting attention. In particular issues of system representation, interdependence and heterogeneity are of central importance in the justification of a microsimulation approach. Additionally the way in which the updating, or dynamics of the system are dealt with is a major consideration with a number of alternative approaches available. These all give rise to a number of practical issues that are addressed in section 3 along with a discussion of computational matters. At the heart of any modelling exercise, of course, there remains a fundamental problem: how theory is embedded into the model system. This complex and difficult question is the subject matter of section 2.4 and 3.4.

Before beginning our survey of the methodology an important point should be stressed which relates to the main purpose of constructing models of socio-economic systems using micro-based methods. Simply stated, we are not concerned with the fate of the individual units in our system per se, but with the aggregate effects contained within the system. Microsimulation methods can be seen as one way of solving the problem of moving from a state description at a particular point in time, or before some event, to a state description at some later point, or after an event. It is in this context that the relative merits of microsimulation compared with more conventional approaches should be viewed.

2.2 Representation, interdependency and heterogeneity

Whether models are meant to provide a causal representation of behaviour or are simply intended as a device for the formal description of variability in a data set (an important role of 'static' microsimulation), the modelling process essentially consists of a series of transformations on information. In this respect a major consideration is at what level a system is described, represented and observed. Although considerable efforts have been devoted to the development of theory concerning individual units in economics, regional science and geography, aggregation of behavioural relationships and the specification of models at the macro-level has been the norm in all these disciplines. Associated with this representation is the specification of an OCCUPANCY MATRIX in which the number of members in each of all the combinations of various attributes can be enumerated. For example the number of households who live in census ward 10, own their own home, are in social class B, and who shop in census ward 22 could be identified from the matrix:

$$N_{ij}^{mn}$$

where
i represents origin zone
j represents destination zone
m social class
n tenure group

This is the conventional representation adopted in input-output analysis, spatial interaction modelling, account based population forecasting and so on. However as the analyst attempts to incorporate more information into the state representation to discriminate between different actors this aggregate representation becomes unwieldy and makes considerable demands upon computer storage. Formally the number of elements in the occupancy matrix is given by:

$$E = \pi_{k} \alpha^{k} \tag{1}$$

where α is the number of categories associated with the k^{th} attribute. Even for relatively moderate values of attributes and categories E will be restrictively large. Moreover for any given application a large proportion of cells in the matrix will have zero entries. Finally, using this representation it proves difficult to handle continuous variables like age and income without experiencing considerable information loss through aggregation.

Alternatively a micro-level representation may be adopted. This involves the specification, for example, of a set of attributes for a sample of households and individuals that represent the population of interest. These samples, stored in the form of LISTS on the computer, have a storage requirement that is simply the number of attributes multiplied by the sample size. For applications where there are a significant number of attributes under consideration this storage requirement will be considerably smaller than that of the corresponding occupancy matrix. Furthermore there are no zero entries and continuous variables can be handled with no information loss through aggregation.

The issues of representation are often stated in the literature to be further polarised when the transition matrix is examined. If an occupancy matrix had one million cells then the related transition matrix would consist of one thousand billion cells and render computational analysis intractable. This tends to present a rather naive view of the way in which models are solved and the data used in that process. Methods such as biproportional analysis, spatial interaction modelling and so on often quite adequately deal with large occupancy matrices without ever having to specify the full transition matrix. Only relevant probabilities or transition rates are calculated during model execution and not calculated in advance and stored internally. This is often exactly the same as in microsimulation modelling. Indeed it often seems that in the microsimulation literature the storage efficiency and information loss arguments are used as principle justifications for the adoption of the approach. While this may often be the case, in simulation modelling the analyst is interested in information relating to the joint distribution of attributes over a population. It is the properties of these joint distributions and the nature of the model operations rather than the characteristics of the sample that are the decisive determinants of both the storage efficiency and information retention issues. It is clear that the structure of the dependence between the attributes is the key to the matter. If for example in the extreme case the attributes $x_1, \ldots\ldots, x_n$, were independent in the sense that the joint density function, $p(x_1, \ldots\ldots, x_n)$ could be factored

$$p(x_1, \ldots\ldots, x_n) = \pi_i\, p(x_i) \qquad (2)$$

then the storage of the probability matrix, p, may be reduced to the right hand side of equation 2. This argument will hold in a suitably modified form when partial dependencies occur. In any given application involving many attributes the arguments of efficiency and information must therefore be related to the structure of the model itself. Often considerable interdependencies will exist and a list representation may well be a strong contender on the grounds described above. We shall also comment later on how mixed representations may be usefully employed in spatial modelling.

There are a number of other potential advantages of using a micro-level representation that may be of particular interest in geographical analysis. First, it is possible to store life record information, such as date of house purchase, date of last migration, type of previous job, and so on. This information can then be used in the modelling process and may be valuable in the examination of systems where Markov processes are deemed important. Additionally, in dynamic simulation models it is possible to produce event histories that can be seen as representative 'biographies'.

Another potential advantage, particularly important in policy analysis, is the flexibility of the model output specification. Because there is no prior aggregation model output can be tailored to the requirements of the user, not constrained by the aggregation process. Any potential crosstabulation of attributes under consideration is possible.

Finally, as we shall discuss later in this section the micro-level representation potentially allows for the incorporation of theories that have been developed at that level as opposed to those relating to aggregates of microunits.

2.3 Updating the population

Central to the modelling exercise is the transformation of a state description from one point in time to another. This may be undertaken to examine how a population will change in relation to on-going processes or to assess the response to new policy initiatives. These changes may be sought at the cross-sectional level (before and after) or to account for true dynamical effects over a period of weeks, months or years. In either case attention must be paid to how the characteristics of a population change and the interdependencies so generated. Two main types of interdependencies can be identified: those that affect the individual and those that affect other members of the population. An example of the former is when the obtaining of an additional educational qualification enables an individual to be eligible for certain types of employment; the latter when a decision to search for a new residence implies that there is extra competition for those already searching. As we hope to demonstrate microsimulation is well suited to handling of complex interdependencies in socio-economic systems.

Before any attempts can be made at simulation the first requirement is for a population sample to be obtained at the micro-level. There are a number of possible procedures for obtaining this ranging from surveys to synthetic sampling methods and these are described in section 3.1 below. Assuming it is possible to establish the micro-data base then a suitable approach to simulation needs to be divised. Three main types of approaches can be identified, cross-sectional static aging and dynamic aging, and we discuss each in turn but with emphasis placed on the latter.

Cross-sectional approaches generally address situations where the rules for, or rates of, eligibility for certain events are changed, or where the number of alternative choices available is altered. For example changes in the eligibility for social security payments and the amount paid need to be properly accounted prior to implementation. Because these rules are often complex and relate to a whole set of household and individual attributes it is more convenient to evaluate changes to them using a sample microdata base. Another example would be the way that alternative medical practices generated different hospital in-patient totals. In terms of choice models a good example is in transportation where the introduction of a new mode of travel could influence the existing pattern of travel demand and utilisation. In all these cases the rules or choice models can be specified in the form of an algorithm and the sample population processed through the model. A before and after evaluation can then be readily performed.

Static aging is perhaps the most common approach that has been adopted in micro-simulation studies. Essentially it involves the reweighting of a sample population to reflect exogenously generated forecasts of particular distributions, such as age and sex. For example if it is assumed that the numbers of persons in a particular class will increase by 5 %, then the sample will be reweighted to reflect this. The weighting procedures used normally consists of solving a least-squares on quadratic objective function subject to a number of constraints which reflect the new distribution of attributes. This was the approach used in both MATH (Micro Analysis of Transfers to Households) and in TRIM (Transfer of Income Model) which are referred to in section 4. The basic drawback to the approach is that it does not attempt to model the processes that generate change. As such it is based on a hypothesis that socio-economic change takes place relatively slowly, which may or may not be the case. Furthermore the data for the reweighting routine must have already been generated from some other forecasting exercise.

Dynamic aging of a population aims at identifying the underlying processes of change and modelling them in a consistent manner. In most applications this is achieved through the use of LIST PROCESSING. This involves examining each member of the population in turn to ascertain if they are eligible for a series of transitions, such as giving birth, migrating, searching for another job, and so on. If an individual is eligible then the appropriate conditional probability for the transition or event taking place is used in Monte Carlo sampling. This simply involves drawing a random number and determining if this falls in the relevant probability interval or not. If it does the event is deemed to occur and vice versa. The major advantage of microsimulation in this case is that it allows for the first and second order effects of transitions to be incorporated in a logical manner. For example, if a female was deemed to give birth then a whole number of effects can be handled. The household size will increase by one, the female may be removed from the labour market with a consequent reduction in household income. This may be set off against an increase in social security benefits although expenditure patterns will probably change. Increased household size may invoke a search for a new dwelling unit, and so on. The specification of the conditional transition probabilities can be undertaken in a number of ways, ranging from published look-up tables to being estimated from discrete choice models. Clearly this is an area which is closely related to the theory behind the transitions and events being studied and we return to this topic shortly.

One immediate problem associated with list processing is how to handle interdependencies between individuals who are members of different households and to accomodate within the model processes that are competition based, such as housing and labour systems. This can be tackled in a number of ways. First it is possible to replicate the competition at the micro-level by storing in core memory all relevant actors and designing a competition based heuristic. An example of this is described in section 4.8. This approach can make excessive demands on computer storage and processing time. A more realistic alternative is to identify pools of demand containing individuals or households and aggregating into relevant classes (e.g. housing demand by type of household and type of dwelling unit sought). It may then be possible to solve an aggregate allocation model (e.g. a mathematical programme) and to generate the corresponding probability distributions with which to return to the pool of households and sample to determine the outcome. More complex methods may be used to examine vacancy chain processes (Williams, Keys and Clarke 1986) where contributors to demand may also form contributions to supply simultaneously. Ultimately it will be possible to keep track of all individual relational interactions simultaneously within the computer program using 'pointers' (Holm 1984, Holm et al. 1985). This will overcome most of the above mentioned difficulties but requires considerable computer memory resources at present.

Dynamic simulation through list processing has a number of well known associated technical problems. First the order in which events are considered in the computer program may bias the outcomes. For example if birth is considered before death the total number of births may be overestimated by including those eligible females who would have died. This problem can be surmounted to an extent by reducing the simulation period from a year to a month, and increasing the number of simulations, although this will also increase the computational cost. A second problem relates to the sample size that is needed to satisfactorily reproduce aggregate state distributions at some future point in time. This is further compounded by the existence of Monte Carlo sampling error, where running the simulation models with different random number streams may affect the output (see sections 3.3.3 and 3.3.4). Generally, these problems can be overcome through the use of sensitivity analysis to determine the amount of variability associated with different sample sizes.

In terms of the merits of the three main approaches to updating the population the nature of the application and the type of information being sought will ultimately be the critical parameters as well as the amount of resources that can be devoted to the exercise. As Caldwell (1983) points out it is conceptually more attractive to use dynamic aging to update the characteristics of the population. However, when the simulation period is relatively short (1–3 years) then static aging may be perfectly acceptable.

We now proceed to examine how theories relating to the transition processes may be embedded into the micro-models.

2.4 Embedding theory into microsimulation models

As we have pointed out above the central feature of microsimulation is the modelling of transitions between states over time. This may take the form of an event (e.g. birth), choice process (e.g. choosing a mode of transport) or something more complex, such as a residential or job search procedure. In most cases there will be a number of ways of treating the transition from a theoretical viewpoint. In the simplest case we may obtain transition rate data from published sources, for example the age, marital status and location specific fertility rates from central government. An alternative approach would be to estimate transition probabilities from a regression model (e.g. a logit model) which may be underpinned by some behavioural theory, such as utility maximisation. This is a well established option in such areas as spatial choice modelling. In some cases a heuristic or rule based system may be used to determine the transition probabilities. Good examples of this are found in residential search modelling where a household's criteria for choice may be refined as they search and reject an increasing number of properties and their behaviour changes from maximising utility to satisficing or simply giving up the search. Heuristics may be particularly useful in constrained systems, for example in health care planning models the probability of admission will partly be a function of severity of condition and age but will also be governed by the availability of hospital beds.

We shall return to the issue of model estimation in section 3.2 below.

Having examined some of the main features of microsimulation modelling we can now turn our attention to some of the practical issues that are faced in model implementation.

3 Practical and computational issues in the implementation of micro-simulation models

In this section we examine a number of issues that relate to the practical implementation of microsimulation models. The most important of these are: the construction of a relevant micro-data base; the estimation of transition rates; and simulation methods. We discuss each of these in turn.

3.1 Construction of a relevant micro-data base

Clearly, a primary requirement for micro-simulation models is a micro-data base. In most applications this will consist of a population sample specified at the individual and household level along with an appropriate set of attributes. In some cases the data set may be fully available from primary sources such as the Public Use Sample from the U.S. census. This can then be used directly for some applications. However even when micro-data is available the set of attributes defined may not be sufficient for the analysis which is to be undertaken. Two solutions can be invoked here—iterative proportional fitting (IPF) together with Monte Carlo sampling which is described below, and merging or matching of different micro-data sets. In the latter case we assume that two or more micro-data sets are available, one containing the set of attributes (a,b,c,d) and the second set (a,c, d,e). Assume also that a common attribute definition is used and that they are sampled from the same population. The task is to generate a single data base containing the attribute set (a,b,c,d,e). The statistical matching is performed in such a way that the weighted difference in the common attribute set (a,c,d) is minimized. Techniques for solving this class of problems and incorporating additional information are emerging.

In the worst but perhaps most typical case no appropriate micro-data will be available. In this case there are two possible courses of action. First to undertake a sample, secondly to use synthetic data generation methods. Sampling is usually too costly an exercise to undertake, notably in spatial analysis where a large sample population will be required to enable interaction data to be generated.

Synthetic methods that enable a micro-level population to be generated from aggregate distributions are an appealing way of solving the problem. By incorporating IPF methods to estimate joint distributions of aggregates and then sampling from the resultant probability distributions a population can be generated at the micro-level whose characteristics, in aggregate will correspond with all supplied distributions from aggregate data. A full discussion of the theory of IPF can be found in Fienberg (1970) and a description of its use in synthetic population generation and a set of examples is provided by Birkin and Clarke (1986). As mentioned above it also provides a useful method for ascribing additional variables to a normal microdata set.

3.2 Estimation procedures

Some sources for or steps in validation of models in general as well as microsimulation models could be labelled as follow:

1. a priori theoretical knowledge
2. a priori empirical knowledge
3. internal consistency
4. model performance

1. The main actors and behavioral units behind the aggregate outcome in social science models are individual decision making units. In a microsimulation model they are modeled individually. In model construction this often makes it easier to use theories of individual behavior from geography, economics, sociology, social psychology and other social and behavioral sciences directly. Corresponding theories at the macro level often relate to individual behavior but also to hidden interaction due to the effect of a specific kind of aggregation in the measurement of this individual behavior. This measurement imposed interaction component could not be separated from the behavioral component and therefore those theories sometimes become more of temporary empirical generalisations than genuine theories of, for instance, spatial behavior.

The possibility to formulate the behavioral rules consistent with established theory is a way of increasing the validity of the model.

2. Although in rare occasions it may be possible to formulate and calibrate a model with help of established theory and nothing else, in an applied model we demand higher precision in prediction (and accept a corresponding loss in generality) than what is possible to get from theory only. This kind of required a priori knowledge in the context of micro simulation models typically has the form of a probability function. The probability that a specific individual is going to perform a specific action (to migrate, move together, change job, go to a certain shopping centre etc.) at a specific point in time and space is related to attributes of the individual and his surrounding. This can be formally represented as the conditional probability distribution:

$$P(e|i,t) = f_e(X_{it}, X_{jt}, X_{rt}) \tag{3}$$

where:

i = individual
j = other object (ie. region, firm, school)
r = individual or other object related to individual i
t = time (period)
e = event (ie. migrate, change job, divorce, die, be fired)

a = attribute (of individual or other object).
X_{it} = vector of attribute values $\varkappa ait$ of individual i up to time t (ie. sex, age, race, marital status, occupational status, education, profession, wage).
X_{jt} = vector of attribute values $\varkappa ajt$ of object j up to time t (ie. number of population, number of vacancies or retail floor space in region j).
X_{rt} = vector of attribute values $\varkappa art$ of individual(s) or other objects related to individual i up to time t (ie. parents education, partners wage, size of household, age of children, population in place of residence, quit rate at place of work).

The function f can be formulated as an algorithm with a set of rules or as a simple algebraic expression. In society the action space and the degree of freedom in behavior is heavily delimited by more or less trivial formal and informal normative and logical rules. In this case it is necessary to ensure that these are consistently embedded in the simulation model rather than to calibrate them in any formal way. In Sweden all children have to start school at the age of seven years, a child can't move alone, bigamy is not allowed, certain jobs are not allowed for people younger than 18, others demand specific education, every period in a certain education, employment, marriage, dwelling, home region has an end and must end before the next period can start etc.

In a realistic simulation model these kind of rules take up the bulk of code and variation in behavior. For the more voluntary individual actions within those directions, it is often possible to formulate an algebraic submodel and calibrate the parameters of this function with full maximum likelihood regression techniques.

The obvious ideal database for this estimation is the same one as is used as the start population for the simulation runs. This database should contain a list of records of attributes for each individual and other object that is used in the probability expression. If the expression contains lagged responses (for example if labor market behavior is thought to depend both on current work and education as well as the work and education history of the individual) then the database ideally should be a longitudinal individual panel study with data for several time periods.

Those demands are seldom met in practice. As was discussed in section 3.1 both the construction of the initial micro-data base and the estimation of the probability functions has to be based on a merge of different partial, more or less aggregate data sources.

Ordinary least square estimation is rarely suitable in this setting because, typically, the expression will not be linear in the parameters or a linear transformation would give biased estimates.

Several statistical packages exists (i.e. LIMDEP, GLIM, BMD4, FUNCAT(SAS)) that perform a full maximum likelihood estimation on this kind of regression functions either by help of some kind of Newton-Raphson iteration scheme or by iterative proportional fitting that corresponds to the method of minimum discrimination information (entropy) which in turn can be shown to be almost equivalent to full maximum likelihood estimates (Amemiya, 1981, Maddala, 1983).

3. A collection of rules and an estimation of partial probability equations give some of the material to put together in the actual model construction. The next test is to see if and how the pieces fit into the decided structure of the model. One common experience from the construction of large microsimulation models is probably that they do not fit at all in the beginning. The model will not run at all. When it does, after several revisions, and begins to produce results those are completely wrong even if the criteria for judgment in this phase is nothing but the subjective notion that they should look "reasonable". When this criteria is fulfilled and it is no longer possible to trace apparent mistakes just by looking at the output it is probable that both the main structure and lots of details are completely different as compared to the first version.

The point is that this "software development phase" is something completely different from a simple and mechanistic translation of a conceptual and estimated model to executable code. In fact, this phase is often the most important part in the validation of the model.

"The whole is more than its parts" is a trivial but nevertheless often rediscovered fact. In a way one can say that the observed processes of the real world is one out of several possible event histories. A model tries to replicate parts of those processes. Within this limited model world it is also possible to produce event histories that could never be observed outside the model. Inside it's limited scope the degree of variability is bigger than outside because many of the restrictions in the real world could be more or less unconsciously released. But it is harder to dismiss restrictions in a big and detailed model as a micro simulation model easily could emerge into. When the debugging process demands the specification of a certain interaction we take the best available from knowledge and experience. In this process the degree of variation in possible output is significantly reduced. So, if a big model system works smoothly without apparent internal inconsistencies this in itself means that the model is more valid than was its parts before fitting together.

One consequence of this is that it is important for both model building and validation to have a good programming language that among other things supports a modular development and easy overview over the entire model as well as over details in its parts. It is also important to have a good programming surrounding with libraries of pretested program modules and debugging tools.

These program development tools are equally important for the construction and validation of the model as is a good and valid database, theoretical knowledge, statistical packages and reliable estimates of behavior relations.

4. One important test of any model is its predictive power. Sometimes a simple macro trend extrapolation hits the target better in the short run than does a more elaborated model. In the short run most processes change just a little. In a time perspective where structural changes might happen, when explanations are sought and when the model is intended to be used for experiments to test the effect of policy parameter variation then the elaborated model is inevitable. Still it should be capable of smoothly replicating real processes to be useful.

A straightforward way of testing the model on historical data is to use the first periods of a longitudinal database to calibrate the model (fit set) and thereafter compare the projections of the model with data for the last period(s) (prediction set). This method presupposes both a long term stability and a high degree of completeness in the assumed causal network as well as very clear assumptions of what factors should be supposed to be exogenously determined. While this would be nice from a theory development point of view it is perhaps too much to demand from every (short term) policy model.

There are also other schemes of testing performance available, potentially of use in microsimulation that make use of contemporary data(periods) only. One idea (the crossvalidation approach, Wahba 1977, p. 607–623) is to delete the observations one by one, every time calibrating the model with the rest of the data set and use the model to "predict" the dependent variables for the deleted observation. This is repeated for every observation and thereafter it is possible to compare and test the difference between all the calculated and observed values.

So far it has been assumed that every parameter of the model has been calibrated in advance; statistically, theoretically or "logically". The performance test then gives an overall measure of the resulting goodness of fit for the different variables in the model considering also all interaction specified in the model structure but not affecting the separate statistical parameter estimates.

Often however data for such calibration prior to model execution has not been available firstly, even for observable behavior (move together without marrying). Secondly, even when there is lots of data on actual behavior (geographical mobility) nearly nothing is registered on the corresponding decision process (decision to move) and information processes (perceived availability of jobs in other areas). Thirdly, in some cases we want to use theoretical concepts that are not directly observable themselves but nevertheless useful in theory and model formulation (like supply, demand, intention, saturation, skill, satisfaction, ability, context, surrounding etc.). Fourthly, most rules and algorithms formulated in a model are informal and could only be based on the model makers experience and prejudices.

For all those variables and corresponding parameters and rules the simulation model as a whole could be regarded as an estimation device. Those rules and parameters for unmeasurable variables are varied in a systematic fashion so as to minimize the prediction error with respect to the observable and measurable variables.

If it is the question of a single rule or parameter this can be done systematically. The simulation run is repeated for a range of parameter values or for (all) different formulations of the rule and the one that gives the smallest prediction error is chosen.

However when several rules and parameters are considered it is not possible to test all combinations of values. Sometimes, if the model is very simple, it might be possible to use an iterative solution technique like the Newton-Raphson method in full maximum likelihood estimation programs or the iterative proportional fitting method used in entropy models. All the model is then regarded as a black box, a function that delivers a certain scalar response indicator value (an overall measure of predicting error for all variables) for each combination of parameter values and rules. As each evaluation of this function demands a full simulation run with the model it might be quite expensive to run the iteration until convergence.

A weaker alternative to iteration is to use some new heuristic method that uses rules of thumb for choosing new combinations of parameter values to test. Because of the possibility to formulate those rules in accordance with preconceived knowledge of interaction between and importance of parameters this method might demand a smaller number of model evaluations before convergence. On the other hand the risk of remaining in a local optimum is also bigger.

A seemingly important complication for this kind of calibrating simulation models is the random variation in the predictions due to the Monte Carlo method of updating the attributes of the objects. This random variation might produce different parameter estimates due to what sequence of random numbers has been used. The stocastic variability in the response might be bigger than the systematic difference between different parameter combinations while approaching convergence.

On the other hand, if the overall model specification is reasonable, this random variation between different runs is a good estimate of the predicting error in the model. It depends on genuine uncertainty and lack of knowledge and demonstrates the limits of the models predicting capabilities. If so, there is no point in using a finer convergence criteria than this average error in the distribution of outcomes of model runs. This means that "convergence" is rapidly approached and certainly could be approached with different combinations of parameter values and rules. The conclusion is that they are "equally" good.

It is not possible to discriminate between the parameter values and rule formulations within this set with the data and model specification used. This is in itself an important result that is often hidden in the "optimal" solutions produced by deterministic models.

3.3 Programming languages

Usually little attention is paid to the choice of programming language to use for implementing a simulation model. In many applications this is quite adequate. The problem could be formulated and executed in any language. Other applications however could hardly be managed without help from the facilities in some special modern languages. The following table tries to describe the relation between some of those types of applica-

kind of model	important capability, typical data structure	example of language or package
1. small system of diff. equations (economic macromodel)	easy and rapid prog. development, vector	basic, apl, spreadsheet
2. big system of diff. equations (reg. ec. macro model syst., weather forecasting model or timedriven microsimulation model with record attributes only like in MATH, KGB, DYNASIM)	efficient number crunching and i/o to external-memory bound databases, matrix or list of records of numerical attributes	fortran, algol
3. timedriven microsimulation model with pointer attributes	pointer to record	pascal, C, ada, modula2, pl1
4. eventdriven microsimulation model (HÖMSKE)	corutines (pseudo-parallel processes), object	simscript, gpss, simpl1, simula, ada lisp, smalltalk, C++
5. eventdriven microsimulation model with a "production system"	expert system shell with a rule base, "context" and interpreter	lisp, prolog, simula, C++

tions, important facilities and usable languages and packages:
The first category of applications, features and languages is strictly spoken outside the range of micro-simulation models but sometimes the execution of such models is referred to as "simulation".

The second category contains the major well-known applications of microsimulation technics on population systems. The typical data structure is the list of records of attributes of each individual. In those applications it is possible to represent each attribute with a numerical value for sex, age, race, income, education level, type of region etc. For this purpose the record structure of Fortran is sufficient. Moreover, those models are often connected to other macromodels and then it is convenient to use the same language as is used in those—usually Fortran.

The third category of models represent an ambition to further individualize the representation of the individual (object). Not only the individual but also the different relations between individuals are modeled individually.

A person is not just married, but married to a specific other individual, technically represented by a pointer (labelled husband) to the address of the record of that specific individual. The person lives in a specific region and when he moves the value of the pointer ("region") is changed to the address of another specific region. As discussed elsewhere this ensures internal accounting consistency within the model.

In the fourth category the decision making unit is still more individually pictured, not only existence and relations but also rules of behavior are individualized and connected to each individual (object). In the former categories, modeled with help of procedural languages, there is a strict delimitation between data and code. The individuals are individual only with respect to passive data representations of attributes and relations. Then there is one main program deciding how and when those attributes are going to change.

In an object language representation the individuals are partly selfsufficient with (pointers to) "own" code. An individual "decides" for himself when to move from home, search for job etc. The individuals live "their own lives" but are continually interacting with each other, sending, receiving and reacting on messages.

A metaphor for the object representation of the individual could be a small computer. Each individual could be represented by a small computer with it's own data *and* code but also connected to other small computers in a network. As time goes by each object (individual) runs his own program and behaves accordingly but the individual programs could any time be interrupted by signals from outside and react by switching over to an other program i.e. respond by a changed behavior pattern.

One individual is, say, repeatedly searching for a new job. Suddenly he receives a message that he has got one of the jobs he applied for. Then he disconnects (or reduce the intensity in) his job seeking routine and switches over to a negotiating and thereafter eventually to a working routine.

In this kind of realistic representation of individual actors it is easy to concentrate on assumptions of determinants of individual behavior while the simulation system takes care of the administrative burden of scheduling the actions of the different individuals on the time axis.

Finally, as mentioned earlier it is often more easy, natural and closer to experience to formulate behavioral assumptions not as algebraic expressions but as an algorithm using a set of heuristic rules guiding the actions of the actor. Such rules often have the form: "If such-and-such condition holds, then such-and-such action is appropriate". The action could be to search for and evaluate another rule, i.e. to prolong the decision process of the actor in the model. So before any "real" action is performed a complicated, nested set of elementary rules could have been evaluated. The choice of rules and the order in which actions are performed is then determined, among other things, by the outcome of the application of the previous rules.

A systematic way of expanding the representation of knowledge or causal structure is to use some constructs developed in the AI-research that has produced expert systems (For a discussion of the use of such a framework in spatial behavioral modeling, see Couclelis, 1986). In a "production system" the "production rules" are contained in a rule base. The "context" of the actor is a data structure containing that subset of the conditions in the different rules in the rule base that for the moment are relevant for the actor. If the conditions of one or several rules are present within the context of the actor then those rules are sent to the "interpreter", which is a routine deciding which of the rules to apply (Barr and Feigenbaum 1981).

With this representation not only the variables and parameters but also that main part of the causal structure of the model contained in the rule base are separated from the main code of the program. Thereby they can be treated in the same way as data and easily changed. Even for the program itself it is possible to modify that data. The actors in the model could learn by experience so that the rules they apply on themselves change during execution.

The user of the model could "replace" one of the actors in the model. Then the model can "learn" about the production rules by making inference from the decisions performed by that human user in interaction with the model during execution.

3.4 Monte Carlo sampling

There is no difference in aiming to make a model as "deterministic" as possible between a simulation model using Monte Carlo sampling in determining outcome of choices and a model using expected values in assessing outcomes of behavior equations. The difference is that with Monte Carlo sampling this undeterminable part of the variation is explicitly internalized in the model and not hidden in expected values without error distributions. Such a deterministic formulation is like pretending that the model contains full information so that any event or action prescribed by the model has the probability 1 and all the other (possible) event histories has the probability 0.

In short, the Monte Carlo approach has at least two advantages. First, the distribution of outcomes from repeated runs of the model gives a good picture of the predicting power of the model. Secondly and even more important, most combinations of event histories for individual objects are unique. The "expected value" formulation could not represent combinations that "on average" are performed by less than one object although those together make up most of the event histories actually performed.

3.5 Variance reduction

A micro-simulation model is often constructed as an aid for policy analysis. Then, the main purpose is to study the distributional impact on the population by a change in, for example the rules for or amount of tax deduction, subsidies, allowances or credit support. Typically it is of interest to compare the outcome of the existing rules with one alternative. Then, it is sometimes said (see for example Orcutt et al, 1976), that the Monte Carlo sampling adds an error component to the systematic difference between the base and the experiment run. This in turn unnecessarily increases the needed size of the base population sample in order to receive significant differences in outcome for different population groups of interest.

One suggestion to reduce this "added" variance is to use the same sequence of random numbers both in the base and in the experiment run. The idea is that all choices, actions and events not directly influenced by the changed rules should be the same in both the runs. Then only the systematic component caused by the changed rules would be seen in the results and hence the sample size needed for obtaining significant results would be smaller.

The idea is correct if its assumptions are. The random numbers are produced by some algorithm producing exactly the same numbers each time it is started with the same "seed". The next assumption is that those numbers will be applied to exactly the same events at the same times for the same individuals in both runs. Apparently this will be the case if nothing is changed between runs. The 1234567's number is 0.03 and causes person number 7000 to leave labor force in the fourth simulation year in both runs.

Suppose that one policy to be changed in the experiment run is the amount of subsidy given to industry for keeping up employment. One way or another this might reduce the probability to become unemployed for person number 7000 below the 0.03-level and so he will keep his employment status that year. Now two different things might happen depending on how the model is formulated. Let us say that the person in question in any model type now and then evaluate vacancies in the labor market. In a simplistic model the probability to apply might be increased if he is (has become) unemployed, but the evaluation as such is undertaken exactly at the same time and in the same order as before.

In a more elaborated model there might be a specific job search algorithm invoked just for people recently becoming unemployed (with a wider search profile over professions and regions). This evaluation is then using the random number that otherwise would have been used for evaluating the "next" event for that specific individual. After that single "accident" every forthcoming evaluation is done with another random number than is used in the base run. With several such conditional algorithms interacting via the individuals over time the correspondence between number of random number and event becomes totally unpredictable.

Therefore, the idea works if exactly the same events are evaluated in the same order for the same individuals each year regardless of the outcomes of those evaluations. After his death a person must continue to evaluate his (hopefully nonexisting) possibilities to start an education, enter the labor force, marry, move, die (again) etc. until the very last simulation year. The same holds for all not yet born children that are going to be born before the last simulation year!

In some technical simulations and in very simple static micro simulation models those assumptions might be possible to maintain. In a dynamic model it soon becomes very clumsy and inefficient not to use information about what has happened to disconnect evaluations that are totally irrelevant in the actual situation of the individual here and now. In an event driven simulation it is the stream of performed actions and events rather than year, person number and event order that determines what and when to evaluate next time.

So, for most interesting applications to come variance reduction via identical sequences of random numbers is out of the question. As discussed earlier, if the systematic effect of a new or changed policy measure is smaller than the mean distances between outcomes due to lack of knowledge then this tells us that the benefit for some groups might be hidden by the effect (in any direction) of other more important but unknown factors. Even so it is of interest to determine the size of the systematic impact. The classical, but in this case expensive, way of reducing the internal variance still remains—to repeat the base run and the experiment run a number of times.

4 A review of applications

4.1 Dynasim

Orcutt's contribution to the development of microsimulation methods in economics and demographics cannot be overstated. For three decades he has been advocating their use in the best way—by example. Although it is difficult to single out his most important specific contribution many would suggest that the development of DYNASIM (Dynamic Simulation of Income Model, Orcutt et al. 1976) is of particular note.

DYNASIM was the Urban Institute's successor to TRIM (Transfer of Income Model), a static micro-simulation model, although its pedigree can be traced back to the early 1960s (Orcutt et al., 1962). DYNASIM is a true dynamic model that simulates the economic and social behaviour of households over time. The following events or characteristics are simulated:

> (i) Birth (ii) Death (iii) Marriage (iv) Divorce (v) Geographic location (vi) Education (vii) Disability (vii) Labour Force Participation (ix) Hours of labour supplied (x) Hours of unemployment (xi) Wage rate (xii) Job change (xiii) Employment sector (xiv) Income from Govt. Transfers (xv) Non-Social security pension benefits.

For each of these events a large number of determinants were included in the transition probability computation. For example the probability of job change was taken as a function of age, race, sex, education, tenure and sector of employment. Additionally DYNASIM included a relatively simple macro-economic model of the U.S. economy to determine factors such as the overall unemployment and wage rates which could be fed into the micro-level operating rules. The need for system closure in this fashion is a common feature in micro-simulation models (Clarke and Wilson 1986).

There are three main types of output from DYNASIM. First, straightforward aggregate tabulations such as total births and deaths in each year of the simulation. Secondly, any potentially interesting cross tabulation can be specified (because of the micro-level specification). Thirdly, longitudinal histories can be produced for sample individuals in the population.

Applications of DYNASIM, like TRIM, have mainly concerned the examination of the cost and distributional effects of transfer income policies. For example the effect on the AFDC (Aid for Dependent Children) program was examined by Wertheimer II and Zedlewski (1978).

Spatial representation in DYNASIM is crude. Only four spatial units were identified, dividing the country into coarse sectors. Refinements to this readily suggest themselves and are discussed in the section on the KGB model below.

4.2 Housing system analysis

A number of workers in housing system research have recognised the potential benefits of using microsimulation methods. Most notable of these is the HARVARD URBAN DEVELOPMENT SIMULATION MODEL (HUDS) developed by Kain and Apgar (1985). HUDS is a dynamic disaggregate disequilibrium model of a metropolitan housing system. The demand side is represented in terms of age, race, occupation, labour force status, and workplace of the head or primary worker, in addition to the income, tenure, size and years of residence of the household. Eleven variables were used to represent the supply side, including location, structure type, neighbourhood quality and so on. Indeed it is this level of disaggregation and the corresponding heterogeneity in the housing system that were principle reasons for adopting a micro-level representation.

HUDS consists of seventeen separate sub-models that simulate various aspects of housing dynamics in a city. Pools of movers on the one hand and available supply on the other are created and a linear program solves the allocation problem as well as outputting shadow prices which can be interpreted as locational rents. The model has been implemented for Chicago for the period 1960–1970 using a sample of over 70,000 households and dwelling units. It has been specifically used for assessing the effects of spatially concentrated programs such as CHIPS on housing and neighbourhood improvement. The model operated with an explicit spatial dimension—some 200 residential districts were identified along with 20 workplace locations.

A number of other housing models have been constructed using microsimulation methods. Wegener's model of the Dortmund housing system (Wegener 1981) and that of Clarke, Keys and Williams (1981) were both motivated by representational considerations. In the latter case the facility to incorporate longitudinal data into the household attribute list was also considered advantageous.

4.3 The KGB microsimulation model

The KGB model, named after it's developers Richard Kasten, David Greenberg and David Betson (1980), is probably the best known example of an applied static micro-simulation model. As a discussant of the model (Edward Gramlich) pointed out: "If the KGB performance is comparable in other areas, the CIA has big problems". The model was developed in order to give decision support for the Carter administration's Program for Better Jobs and Income (PDIJ) which was quite a complex package of income and job distribution policies. The model has been used by the Department of Health, Education, and Welfare, the Department of Labor, and the Congressional Budget Office to calculate the costs and effects of the proposed alternatives in PBIJ to the former welfare system.

The model builds on earlier attempts, firstly "RIM" (Reforms in Income Maintenance) that was developed by the President's Commission on Income Maintenance Programs 1969. Further developments by the Urban Institute resulted in an updated, modular version named "TRIM" (Transfer Income Model). Later improvements at Matematica Policy Research ultimately ended up in a model known as "MATH" (Micro Analysis of Transfers to Households). Some of the routines in TRIM and MATH were then adopted in developing the KGB model about 1977–1978.

The model works in four steps, firstly, the pre-reform socioeconomic status of the population in the sample is characterized. All of this information could not be read directly from the input data, taxes paid and tax rates were derived from schedules, amounts of unemployment compensation in current transfer programs were estimated etc. Secondly, net wage and disposable income are adjusted to what they would be if the new policy were implemented *if* desired hours of work and earnings remained unchanged (the older models ended at this point). Thirdly, labor supply response to the changed wage rates and incomes under the program are calculated, thereafter the new resulting disposable income is calculated. Fourthly, it is determined whether an individual will take a program job whenever he is in the labor force, only when he is unemployed, or not at all.

The earlier models (RIM and TRIM) had nearly no behavioral responses built in, they were just means of processing income data and adding up program costs after upplying the changed rules on each individual in the sample. "People would just take their income maintenance payments and continue supplying exactly the amount of labor they supplied before the program." In contrast the KGB model, among other things, contains labor supply responses to net wage rates and family income as estimated in the Seattle-Denver Income Maintenance Experiment, workers allocate themselves to public or private employment based on expected earnings in both sectors over the next ten years, those who choose private employment get another choice of whether to take the guaranteed public job or their unemployment payments every time they become unemployed, firms losing low-wage workers to the (better paid) public sector raise their own wage rates, everybody has a choice of how often and how long to participate in the guaranteed employment program or in the transfer payment program.

Apart from the routines that simulate changes in tax and transfer policy, participation in guaranteed employment programs, responses regarding work effort when wage and income changes etc. the model requires a big micro data base with data on individuals' wage rates, hours of work and a lot of other socio-economic attributes. The KGB model used the 1975 Survey of Income and Education (SIE). This sample consists of nearly 200,000 households.

The single most unique aspect of the KGB-model compared to its predecessors is the simulation of a guaranteed job program. The individual is supposed to make a choice between three alternative strategies: (I) the "private strategy", where the person does not participate at all in public employment, (II) the "mixed strategy" where the person works in the program jobs only during periods of unemployment, and (III) the "pure strategy" where the person works only in the public program jobs. For each person, hours of work are calculated for each strategy and based on his earnings and disposable income. Then the person is supposed to select the strategy that yields the largest disposable income.

Although elaborated, it is of course easy to find objections against this procedure. The optimization of expected disposable income is close to the optimization of utility prescribed in choice models derived from economic theory although the concepts of satisfaction under limited information about choice alternatives in the opinion of many social scientists gives a more realistic framework for modeling actual behavior. Another problem, pointed out by Raymond Uhalde is that the labor supply functions estimated in the Seattle-Denver study might not be relevant for the KGB-model application because they were estimated on a ordinary market with constraints on the demand for labor yet they are applied in a program where the demand for labor is infinite at the program wage. This presupposes that there were no "discouraged worker" effect present in these estimates. The authors themselves estimate that this effect might give a considerable underestimation in the number of program jobs. From at least a Swedish perspective with a fairly equal distribution of disposable income the objection is rather that wage and income are hardly the most important determinants of individual labor supply among those available in the micro data base.

The major task for the model was the calculation of program costs and number and characteristics of the potential participants in the proposed public employment programs. For example results like: "had the Program for Better Jobs and Income existed in 1975, 35.7 million people or 17 % of the total U.S. population would have been eligible for cash payments of $22.4 billion". Of those eligible, for various reasons, only 28.4 million people or 80 % actually would choose to participate in the program.

We can now ask: (1) to what extent have the model makers incorporated factors where the regional variation or the regional interdependence has an important impact on the (aggregate) result and (2) to what degree could and have the results been presented regionally? It is nearly self-evident from a geographer's point of view that the latter question is of interest, but this interest in turn derives from a belief that most important driving factors and restrictions are faced to spatial variation and interaction. Therefore it is important not to disregard spatial heterogeenity in inputs (1) whatever perspective one might have on the aggregate results (2). As mentioned in the beginning of this paper, for a geographer, one of the most appealing characteristics of micro-simulation methods, is their ability to incorporate detailed spatial heterogeenity in a consistent, yet simple fashion.

In the micro data base used (SIE) it is possible to locate the households to 146 distinct geographic areas, 96 large SMASs and the 50 states. Moreover, the subsamples for each individual state are supposed to be "statistically reliable". As the authors says: "This is particularly important because of concern over the fiscal impact that various welfare reform alternatives will have on individual states and interest in the state-by-state distribution of the demand for public employment". This statement seems to imply that one goal with the model was to produce results at least on a state level although no such tables are presented in the written article (Betson et al., 1980).

One comment about the regional distribution of calculated full time year equivalents ("slots") of public service employment (PSE) goes: "The number of PSE slots among census regions varies markedly and reflects regional distributions of wage rates and unemployment. For example, 37 % of the participants and 38 % of the slots would be located to the South (as compared to North east, North central and West).

It is also useful to note that almost two thirds of the total slots going to the South are for pure participants, while more than half of the total in the rest of the country are for mixed participants. This difference mainly reflects the relatively high proportion of southern workers who are paid less than the minimum wage" (and thus eligible for PSE).

So, while perhaps not used so, the model and its database allows a rather detailed regional description of labor supply adjustments to welfare reform programs. It is presently not possible, however to "take into account other behavioral responses, such as changes in marital stability and geographic mobility patterns." Such extensions however might not be easily incorporated in the static model framework of the KGB-model. These kind of interactions take time and have side effects that are much easier to represent in a dynamic micro model.

As for the regional variation in input the most important part is automatically taken care of by the fact that the attributes of the individuals are registered and modeled on a household level. As the sample is representative also for the individual states at least the state by state variation in attributes should be represented accurately in the model. Probably this also holds for state by state variations in tax rates and rules as well as for current benefit levels of transfer payments. The latter varied dramatically across states, from $6132 for a family of four with AFDC and food stamps in New York to $2556 for such a family in Mississippi. As one of the main goals for the welfare reform was to narrow this range the regional variation in those rules and payments should have been accounted for in the model.

On the whole, mainly because it is built upon such a big sample, the KGB model gives unusually good possibilities for a detailed regional account both on assumptions and results, at least regarding its central factors; wage, income, transfer payments, number and characteristics of participants in public service employment in a short time perspective. The ambition to extend the model to simultaneously model household formation and dissolution, local segmented labor markets, migration, effects of other social programs as day care and health insurance probably demand a dynamic reformulation with much care allocated to the formulation of interregional interdependences. Such a model is on the other hand much more expensive to run if comparable in size and resolution and the added consistency and range of results might not necessarily be needed for answering question about the immediate crossectional impacts on participation and income of program changes.

4.4 Longitudinal modelling: SFB 3

The micro simulation model of the Sonderforschungsbereich 3 (Sfb 3) aims at describing the income distribution between individuals and households in a disaggregated manner (see Galler & Wagner, 1986). The base model that was finished in 1980 contains modules for birth, death, marriage, divorce, household formation, labor and capital supply, occupational mobility, unemployment, factor income, taxes and transfer income, consumption, savings and wealth. This Dynasim type base model or the "dynamic cross sectional simulation" model has mainly the same behavioral assumptions and modules as have two special purpose versions of it: the static cross section simulation model and the dynamic longitudinal simulation model. Like the KGB-model the static version does not age the population period by period but might adjust the weights of its micro units.

In the dynamic longitudinal model (Hain & Helberger 1986) just one single birth cohort is simulated from birth to death. The reason for developing this version is the necessity to simulate the entire life cycle to determine distributional effects of say pension reforms or education transfers. This could of course also be done with a cross-sectional model but then one would have to let the model run for nearly a hundred years, simply to receive a single cohort to evaluate from the series of individual cross sections. It is much cheaper to carry out the simulation just for that cohort.

This means that the actions of the individuals in the model has no impact on other individuals. It is not possible to model interactive market or matching processes. For instance, the potential spouses in the marriage process do not even exist in the simulation when the cohort member (alone) decides to marry, the biography of the spouse has to be generated retrospectively. In short, even if the main part of the assumptions is formulated only in terms of individual attributes obvious inconsistencies will develop if the updating of attributes are not at least to some extent dependent on what happens to other individuals. Still, for some specific conditional simulations where it is possible to disregard from most of the social behavior of the cohort members this method could be justified.

There is no sign of spatial differentiation (not even mobility is modeled) neither in inputs, calibration, assumptions nor in output of the Sfb 3 model.

4.5 Innovation diffusion and time geography

One of the first well known spatial applications of simulation of the behavior of individual actors is Hägerstrand's (1952, 1967) model of the spatial diffusion of innovations. In one application he studied the diffusion of acceptance by the farmers of an attempt by the Swedish government to persuade them (with a subsidy) to abandon the custom of allowing cattle to graze in the open woodlands during the summer months (because of damaged young trees and seedlings). The empirical diffusion pattern was compared to a simulated one. The spread of this acceptance was thought to be dependent of (1) the individual farmers resistance to accept the new habit, (2) the intensity and location of personal contacts with other farmers. The latter was modeled by an information field centered around each farmer who already had accepted the innovation. The distance decay in contact intensity was calibrated by help of migration data.

The information field was transformed to a probability distribution and the person to contact each period was chosen by the Monte Carlo method. A second drawing determined whether the contacted person accepted the new idea depending on his individually assigned resistance and the number of earlier not successful contacts. If he accepted he thereafter belonged to the population of innovators spreading the idea within his personal information field. Over time as more farmers had accepted the idea the chance of hitting a person not yet persuaded decreased as a consequence of the rate of diffusion.

The general empirical, temporal and spatial pattern of the diffusion process fitted quite well to the simulated one with those simple behavioral assumptions so this early attempt gave rise to lots of innovation diffusion studies in Sweden and elsewhere (Törnqvist, 1967, Morrill, 1968).

Later attempts in the "time geographical" tradition of Lund have sometimes produced rather detailed local modelling efforts with the emphasize on the limitations placed on the individuals daily mobility trajectories by the local infrastructure and the matching of time schedules for means of transport, work and services (Lenntorp, 1976, Mårtensson, 1975). Öberg (1976) extended the modelling by introducing assumptions on individual spatial adaptations to patterns of supply points with given capacity constraints. By expanding the model to a national scale, maintaining detailed spatial relations between supply and demand, it was used in governmental planning concerning relocation of public resources.

These geographical studies aim mainly at modelling the evolution of spatial patterns or the subset of possible individual mobility trajectories. As compared to the static and dynamic micro simulation models developed elsewhere the behavioral content within the set of possible trajectories is quite limited while the spatial and temporal mobility restrictions are much more elaborated.

4.6 Health care planning: HIPS

A detailed health care planning model that uses microsimulation techniques has been developed in Leeds by Clarke and his colleagues (Clarke and Spowage, 1985, Clarke et al. 1984). The model known as HIPS (Health Information and Planning System) has been developed for British District Health Authorities (DHAs).

The justification for adopting a micro-simulation approach centres on the degree of heterogeneity shown by users of health care services and the corresponding range of services provided to patients and a variety of possible outcomes. By using a micro-level representation most of this variation could be captured and the analysis of a wide range of policy issues undertaken.

The model has five main components. First the generation of an initial population from aggregate data. The following attributes were considered at this stage; age, sex, race, location, socio-economic status and marital status of individuals; age, sex, marital status, race of head of household, size of household, tenure and location.

The model adds health care related attributes to this list. Space is treated explicitly by identifying the enumeration district of residence. For a typical health authority this would comprise some 200 separate locations.

The second component is a morbidity model which identifies for each individual in the sample any medical conditions which involve a visit to a G.P. or hospital in each year of the simulation. On the basis of age and condition the probability of being a direct in-patient, an accident and emergency case or an elective admission is determined. Demand pools by category are built up and form the input into the allocation model.

The allocation model matches the supply of in-patient care by hospital and specialty to the demand. A heuristic approach is taken which attempts to replicate the real world allocation process, through a priority scheme. When a sample individual is allocated to a bed, the length of stay, operative procedures, discharge type and outcome are all generated and become additional attributes. The cost of care is calculated from a specialty costing model. If excess demand exists in the system then waiting lists form. Aggregation over attributes and cross tabulation allow for a detailed picture of hospital performance to be generated. The fourth component is a Performance Indicatoı package which calculates a wide variety of P.I.s to be output.

A final model updates the demographic characteristics of the population each year. HIPS runs for up to fifteen time periods, normally of one year.

4.7 Household dynamics

A considerably important use of micro-simulation models has been to examine population and household dynamics, whether directly to produce forecasts or indirectly as a component of a broader model, like DYNASIM. Interestingly some of the early applications of the method took place in anthropological studies and historical and sociological demography. This work was assisted by the availability of two software packages—POPSIM and SOCSIM (Giesbrecht and Fiew, 1969) that were microsimulation models of population dynamics. In all this work focus lay on the relationships between constituent members of households and the population at large. A micro-level approach is particularly adept at handling these relationships and interdependencies. In the analysis of demographic events there are often complex relations between a large number of demographic, social and economic factors and it was this that motivated Clarke (1986) to develop a household dynamics model for the Yorkshire and Humberside region of England. This model produced forecasts of the full range of population and household distributions over a ten year period under a wide variety of assumptions concerning transition rates. Conventional population forecasting models are limited in their use by restricing attention to individuals. For many planning purposes (e.g. housing) detailed planning of future supply can only be achieved through a knowledge of changes in demand by households.

4.8 Eventdriven interactive micro simulation: HÖMSKE

This model (Holm 1984, Holm and Öberg 1984, Holm, Mäkilä and Öberg 1985) represents an effort to model population systems while keeping track of important relations between individuals (by individual pointers) and between individuals and "stations" (eg. place of work, school, residence). The 20 or so different actions that the actors in the model can perform (give birth, die, start an education or work, move from parental home, move geographically, marry, divorce etc.) are in most cases preceded by a decision and/or searching process (choose education, work, partner and "apply" for a specific education, work, partner etc.) If other individuals are directly affected by an intended action the decision process is extended to a joint decision i.e. when an individual receives an offer to move to a new position in another town then the outcome partly depends on whether the other members of the family could be persuaded to move. If so it triggers a search behavior, the result of which determines whether all the family actually will move. In turn the search and decision process in many cases is preceded by an information process (eg. get information on vacant positions, appropriate partners etc).

The prescribed causal structure behind the decisions is channeled through three "modal domains"; (can); abilities and restrictions, what actions are available for the actor here and now? (will); the individuals own intentions on preferences regarding the same action (ought to); enforced preferences from other agents (society, neighbourhood, class etc). Within the limits of what is possible the actor does what he wants if it does not diverge "too much" (depending on individual attributes) from what he "ought to" do.

The model is written in SIMULA, an object oriented language in which the rules of behavior are partly "owned" by the actors themselves (like their attributes and relations) and they perform their "programs" independently over time as long as no other individual interfere (as they frequently do). So far it is not possible to run the model with a sample population of realistic size due to the huge amount of relations, decisions and actions assigned to each individual actor (say less than 1000 individuals on a suitable mainframe).

Beside the ordinary tabular output the model can produce written biographies for selected individuals in a stereotype but readable natural language form telling the life story with respect to a selected subset of all actions, decisions and intentions during lifetime. This form of output has proved to be a very usable debugging tool. While the tabular aggregates seems to be quite all right the biographies still shows apparent mistakes in the model constructs.

The model explicitly handles spatial relations in terms of information flows and barriers, residential preferences, some priority to local labor, education and partner markets around each individual. It is not yet calibrated against regional data and it can not produce regional output of any interesting detail until it (or the computers) can run a considerably bigger population than now.

4. 9 Combined macro-micro models

We have argued from the outset that we do not consider conventional aggregate approaches and microsimulation methods as competitors but as complimentary techniques. One obvious advance is to combine them in such a way as to maximise the joint advantages. Explicit combined macro-micro frameworks have been proposed by Caldwell (1983) in the context of demographic and economic interactions, by Eliasson (1985) regarding the interaction between the actors within the production sector and by Clarke and Wilson (1986) in relation to a more general approach to comprehensive urban model building. However in most microsimulation models some resort to aggregate modelling is made either in the context of system closure or to solve an allocation problem.

5 Further extensions of microsimulation in spatial analysis

We hope that by now we have articulated the main features of the approach and some of the existing applications. We now turn our attention to speculating on potentially novel applications of microsimulation in spatial analysis. It seems apparent to us that the possible range of applications is large and includes the following topics:

1. Financial Service

The complexity of the financial services system and its current transformation suggest that microsimulation methods have much to offer. Individuals and households consume a variety of financial services bank accounts, savings accounts, mortgages, insurance credit cards, hire purchase, pensions and so on. In many cases the relationships (and choices) between these sectors are subtle and complex. There is a vast regional and local variation in take up of services and a fascinating set of spatial activity patterns relating to the use of banks, building societies, and so on. The advent of the Automatic Teller Machine (A.T.M.) has revolutionised access to cash and reduced the temporal restriction of bank opening hours. One feature of the financial service sector is that all transactions are spatially referenced both in terms of the user (post-code and socio-economic data) and the supplier (location, time, day, type of transaction, etc). This allows for a detailed picture of activity to be constructed. Currently, in Leeds, we are working on the development of a household model which will link geodemographic characteristics with the demand for financial services and to examine spatial activity patterns under a variety of supply configurations.

2. Backwards microsimulation

All the applications described so far have focussed on forward projection. A contrasting approach would be to simulate backwards over time to reproduce past histories. This approach has been adopted in historical demography (Wrigley and Schofield 1981) using conventional demographic accounting models to examine kinship relations in 15th–18th century Britain. Using microsimulation methods it would be possible to extend this analysis. Births would become 'deaths' and vice versa. The approach would be particularly useful if a very detailed cross-sectional description of a population existed at a point in time and the object was to reproduce that description at some earlier period.

3. Information systems for urban and regional systems

Micro-simulation offers an efficient way of storing information and also provides an excellent accounting framework. As a consequence its use as the basis for urban and regional information systems seems logical. We see information systems not purely as containers of existing data but having an analytic and forecasting component. In this context a micro-data base coupled with a microsimulation modelling framework could be a very powerful tool. We have begun to construct such a system at Leeds called RUIN (Really Useful INformation system) and details can be found in Birkin and Clarke (1986).

4. Regional planning

One obvious future application of spatial micro simulation constructs lies in the area of regional labor market and population projections. Most contemporary disaggregated macro models used all over the world are quite crude and do not handle the labor market with a reasonable resolution jointly in terms of regional and professional sub-markets, feed back from supply to demand and interaction between change in labor demand, household composition and spatial and professional mobility. In Sweden one on-going project aims at developing such a micro simulation model with individual representation of persons and places of work.

5. Rule based simulation

The movement towards a more and more object oriented representation of the actors in the simulation models increases greatly their ability to incorporate realistic individual behavioral assumptions. As stated earlier those assumptions are often easier to formulate in terms of rules as opposed to algorithms. Seppälä and Holopainen (1986) gives a recent example of such a model with an embedded rule base for analyzing the migration dynamics in the Helsinki region. One step in increasing the usefulness of such models as a research and development tool is then to make it possible to maintain and elaborate the rules outside the main model, to be able to treat the rules in some way as "data" in a separate data base. This rule base then will contain the main part of the causal structure in the model. So, most changes in assumptions could be performed just by editing this database. Another important extension would be to make it possible to trace the applied rules behind any sequence of events in a model run in the same way as it is possible to ask an expert system about the "reason" (that is applied rules) behind a suggested solution. Such a facility would greatly enhance the development potential of object and rule based micro simulation models.

Conclusion

In this article we have focussed upon presenting the main features, advantages and drawbacks of microsimulation modelling in an applied social science context and also pointed at some performed and future applications in spatial analysis. Apart from a few path breaking developments (e.g. Hägerstrand) most well-known applications so far are found outside social and economic geography. This we believe is an odd state of affairs since the methodology of micro simulation is well suited for modeling spatial interaction and development.

As compared to other social science the geographer more often wants to divide the observations into a number of spatial units and therefore the amount of information required to represent the system adequately increases correspondingly. In the trade off between high spatial resolution and a detailed and accurate description of the social phenomena that varies spatially the latter has often been the loser in geographical analysis and modeling. A micro-modelling approach releases this restriction to a great extent.

With micro-modelling it is possible to use and formulate theoretical concepts and hypotheses about social action on at least the same level of detail as sometimes found in other social sciences without neglecting the apparent and important elements of spatial interdependence seldom found in studies outside geography.

References

Amemiya, T., 1981: Qualitative Response Models: A Survey. *Journal of Economic Literature.*

Barr and Feigenbaum, 1981: *The handbook of artificial intelligence. Vol.* 1., Los Altos. Heuris Tech Press., Kaufmann.

Betson, D., Greenberg, D. and *Kasten R.*, 1980: A Microsimulation Model for Analysing Alternative Welfare Reform Programs for Better Jobs and Income. In *Microsimulation Models for Public Policy Analysis, Vol 1., Distributional impacts,* Academic Press, New York.

Birkin, M. and *Clarke, M.*, 1986. RUIN—Really Useful Information—for urban and regional analysis; methods and examples. Paper presented to the *British section of the Regional Science Association, Bristol,* September 1986.

Caldwell, S. B., 1983: Modelling Demographic economic interactions—micro, macro and linked micro—macro strategies. *Socioeconomic Planning Sciences* 17: 365–372.

Clarke, M., 1986: Demographic Processes and Household Dynamics; a microsimulation approach. In *Woods, R.* and *Rees, P.*, eds.: *Population Structures and Models.* Allen & Unwin, London.

Clarke, M., Forte, P., Spowage, M. and *Wilson, A. G.*, 1984: A strategic planning simulation model of a district health service system: the in-patient component and results. In: *van Elmeren, W., Engelbrecht, R.* and *Flagle, C. D.*, (eds.): *Systems Science in Health Care.* Springer Verlag, Berlin.

Clarke, M., Keys, P. and *Williams, H. C. W. L.*, 1981: Microsimulation. In: *Wrigley, N.* and *Bennet, R. T.*, (eds).: *Quantitative Geography.* Routledge and Kegan Paul, London.

Clarke, M. and *Spowage, M. E.*, 1985: Integrated Models for Public Policy Analysis: An Example of the Practical Use of Simulation Models in Health Care Planning. *Papers of the Regional Science Association,* 55: 25–45.

Clarke, M. and *Wilson, A. G.*, 1986: A Framework for Dynamic Comprehensive Urban Models: The Integration of Accounting and Microsimulation Approaches. *Sistemi Urbani.*, 2/3 pp. 145–177.

Couclelis, H., 1986: A theoretical Framework for alternative models of spatial decision and behavior. *Annals of the Association of American Geographers,* 76(1): 95–113.

Eliasson, G., 1985: The Firm and Financial Markets in the Swedish Micro to Macro Model—theory, model and verification. *The Industrial Institute for Economic and Social Research,* Almqvist & Wiksell International, Stockholm.

Fienberg, S., 1970: An iterative approach for estimation in contingency tables. *Annal of Mathematical Statistics,* 41: 907–917.

Galler, H. and *Wagner, G.*, 1986: The microsimulation model of the Sfb 3 for the analysis of economic and social policies. In Microanalytic simulation models to support social and financial policy, in *Orcutt, Mertz, Quinke* (eds), *Information research and resource reports, Volume 7,* North Holland.

Giesbrecht, F. G. and *Fiew, L.*, 1969: Demographic microsimulation model POPSIM II. Manual for Programs to Generate Vital Events. *Technical Report No. 5, Project SV-285, Research Triangle Institute.*

Hain, W. and *Helberger, C.*, 1986: Longitudinal microsimulation of life income. In Microanalytic simulation models to support social and financial policy. In *Orcutt, Mertz, Quinke* (eds), *Information research and resource reports, Volume 7,* North Holland.

Hammel, C. A., 1976. The SOCSIM Demographic sociological Microsimulation Program. *Institute of international studies, Berkeley,* University of California.

Holm, E., Mäkilä, K. and *Öberg, S.*, 1985: Time Geographic Concepts and Individual Mobility behaviour. *Paper presented at Philadelphia RSA Meeting, Nov. 1985.*

Holm, E. and *Öberg, S.*, 1984: Migration in Micro and Macro Perspective. In *Scandinavian Population Studies,* 6:1, Stockholm.

Holm, E., 1984: To locate education, employment and residence. *Gerum B, Department of Geography, University of Umeå.*

Hägerstrand, T., 1967: On Monte Carlo Simulation of Diffusion. In *Garrison and Marble* (eds): *Quantitative Geography Part I.* Northwestern University Press.

— 1952: *The propagation of innovation waves.* Lund Studies in Geography, B:4, Lund.

— 1970: Tidsanvändning och omgivningsstruktur. *SOU 1970:14, Bil 4,* Stockholm.

Kain, S. and *Apgar, W.*, 1985: *Housing and Neighbourhood Dynamics: a simulation study.* Harvard University Press, Cambridge.

Klevmarken, A., 1980: On Estimation and Other Problems of Statistical Inference in the Micro Simulation Approach. In *Micro Simulation-Models, Methods and Applications, IUI,* Stockholm.

Leontieff, W., 1951: *The Structure of the American Economy.* Oxford University Press, New York.

Lenntorp, B., 1976: *Paths in space-time environments.* Lund studies in Geography, Lund.

Maddala, G. S., 1983: Limited-dependent and qualitative variables in econometrics. *Econometric Society Publications* No. 3, Cambridge University Press.

Morrill, R. L., 1968: Waves of spatial diffusion. *Journal of Regional Science* 8: 1–18.

Mårtensson, S., 1975: Time use and social organization. *Rapporter och notiser nr. 17, Dept. of Social and Economic Geography,* Lund.

Öberg, S., 1976: *Methods of Describing Physical Access to Supply Points.* Lund studies in Geography, B:43, Lund.

Orcutt, G., Greenberger, M., Korbel, S. and *Rivlin, A.*, 1962: *Microanalysis of socioeconomic systems: A simulation study. Harper* and *Row,* New York.

Orcutt, G., Caldwell, S. and *Wertheimer* II, *R.*, 1976: Policy exploration through microanalytic simulation. The Urban Institute, Washington, D.C.

Seppälä, Y. and *Holopainen, A.*, 1986: A knowledge based microsimulation model for analysing migration dynamics in the Helsinki region. Paper for the *8th European Conference on Operation Research,* Lisbon, Portugal, Sept. 1986.

Tinbergen, J., 1939: *Statistical testing of business cycle theories.* Society of Nations, Geneva.

Törnqvist, G., 1967: *TV-ägandets utveckling i Sverige 1955–65.* IUI.

Wahba, G., 1977. A Survey of Some Smoothing Problems and the Method of Generalized Cross Validation for Solving Them. *Applications of Statistics.*

Wegener, M., 1981: The Housing Market in the Dortmund Region: a microsimulation. In *Voogd, H.*, (ed); *Strategic Planning in a Dynamic Society.* Delft University Press, Delft.

Wertheimer, R. and *Zedlewski, S. R.*, 1978. The impact of demograpic change on the distribution of earned income and the AFDC program: 1975–1985. *Working Paper No 985–1, The Urban Institute, Washington D.C.*

Williams, H. C. W. L., Keys, P. and *Clarke, M.*, 1986: Vacancy Chain Models for Housing and Employment Systems. *Environment and Planning, A,* 18: 89–105.

Wrigley, E. A. and *Schofield, R. S.*, 1981: *The Population History of England 1541–1871: A reconstruction.* Edward Arnold, London.