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A Framework for Dynamic Comprehensive Urban Models: the Integration of Accounting and Micro-Simulation Approaches*

M Clarke and A G Wilson

School of Geography
University of Leeds
Leeds LS2 9JT

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CONTENTS

1. Definitions and objectives

During the last decade, we have witnessed a burgeoning interest in the development and application of dynamic urban models. In some instances this has led to the promotion of competing approaches that use alternative methodologies or scales of analysis. While this can be viewed as a healthy academic situation, it is often useful to take an overview of what is on offer and to suggest ways in which synthesis may be achieved. This can have two main spin-offs: first it may lead to the conclusion that some model forms are special cases of others; secondly, there is the possible bonus that new ideas can be generated, especially in the ways that different modelling styles can be linked. In addition it should also be possible to make recommendations how a mix of modelling styles can be brought to bear in particular applied contexts.

We shall also emphasise the importance of retaining an interest in the building of comprehensive urban models so that it is possible to explore the consequences of the interdependencies between the major subsystems of a city. This is particularly important in the use of dynamic models to study change. In recent years, we have learned of the existence of bifurcation effects and that these need to be understood if the nature of the transformations of urban structure are to be explained. What remains an important research question is the extent to which these transformations are governed by subsystem interdependence or by structured change within subsystems. It is to address this question that we need to continue to work on the task of building effective comprehensive models.

We have already noted by implication the existence of a relatively new range of dynamic modelling methods and it is important to bring these to bear on the task. First, however, we need to specify the system of interest and we tackle this issue initially in two stages. In section 2, we outline frameworks and define variables which will be the basis of a dynamic comprehensive model, noting the difficulties of deciding whether to work with an aggregative or micro-level description. Then, in section 3, we review the nature of accounting concepts which will enable us to stitch together a comprehensive model. There are then three types of contribution to the task of actually building the model which we review in the final preliminaries in sections 4-6. There are in turn: the range of dynamical model building methods available; micro-simulation techniques; and methods for constructing performance indicators, because we want to ensure from the outset that the model not only makes a contribution to understanding urban change but is also as useful as possible in a policy context. We then draw the threads together and make recommendations on overall model design in section 7 and discuss the issues involved in making the model operational in section 8.

2. Elements and frameworks for a comprehensive model

In this section, we draw heavily on the paper by Leonardi and Wilson (1985). We aim to identify the main elements which should be components of a comprehensive urban model and to begin to combine them in a preliminary way in frameworks which will ultimately be constructed more formally using accounting concepts.

The main types of elements can be taken as the population, organisations, the goods and services produced by organisations, the prices of these where appropriate, land and physical infrastructure. It is more helpful to attempt to combine these into subsystems, and the main ones, relatively uncontroversially, can be taken as the housing market, the labour market, industry, services, land and transport. The elements, with some of the major relationships shown, are presented on Figure 1. The elements themselves are represented as rectangles, the relationships between typically have 'allocations' as outcomes - e.g. people to employment and these are shown as ellipses. We can then pull out the major subsystems from this figure, to generate figures 2-6. This is useful in two ways. First, it articulates the set of subsystem models which form the building bricks for a comprehensive model (and they are individually useful in more specific contexts). Secondly, it shows the nature of the inter-dependencies between the major subsystems: they arise through common elements - the 'population' or various population allocations appear directly in four of the five figures (and indirectly in the remaining one - via 'housing stock' in the land market in Figure 5).

It is useful even at this preliminary stage to begin to articulate an algebraic description of a comprehensive model system. This process is begun in Figure 7 and the associated key. The i's and j's represent spatial locations. It is best to think of the superscripts which categorise each of the main types of elements as lists. Thus, w which characterises person type might be thought of as $\underline{w} = (w_1, w_2, w_3, \ldots) =$ (income, class, age, sex, race, ... etc). In any particular model-building exercise, we need to specify precisely what this list is. Its length is usually inhibited rapidly by the dimensions of the algebraic arrays which are created; but this can to some extent be dealt with by using micro-simulation methods as we will see later.

Figure 1 represents a relatively coarse portrait of a comprehensive model system at a cross-section in time. It is relatively coarse because only the most basic relationships between elements can be shown - there is little, for example, on the interdependencies of different industrial sectors. This is an issue to which we must return. We can complete the broad sketch of a framework, however, by showing how to get beyond the cross-section to dynamics. The simplest way to think of this is shown in Figure 8: we have to show how to connect the cross-sections at two times by specifying the mechanisms of change. There are many ways of doing this, ranging from an account of the state transitions of individual elements, through the use of 'mover pools', to comparative static assumptions - taking the new cross-section as a new equilibrium but giving no account of how it is reached in terms of individual transitions. To make further progress with these issues, we need to discuss accounting and methods for dynamical analysis and we do this in the next two sections in turn.

3. Accounting methods: underpinnings for dynamic models

Account-based methods have been used extensively in the social sciences over the last thirty years. The pioneering work of Leontief (1951) on economic input-output models can be seen as the starting point of a field of research that has been extended into demographic accounting (Stone 1971, Rees and Wilson, 1977) and linked economic-demographic models (Caldwell, 1982). The main purpose of accounting systems is to organise information, whether from surveys or models, into frameworks which facilitate substantive analysis, generate performance indicators, and which in turn help monitor social change and evaluate policy. They can also serve a useful role in organising the concepts of a model-based system, ensure internal consistency in the treatment of system variables and sometimes identify missing elements of data. We shall argue, therefore, that an explicit accounting system should underpin any set of dynamic models. This will be particularly important when we attempt to be comprehensive in our analysis of an urban and regional system mainly due to the interdependence between many of the variables that characterise this type of system.

Stone (1971) has argued that accounting systems are identified by the principle of double-entry book-keeping. This implies that the inputs into any socio-economic system must exactly equal the outputs, in other words a set of conservation laws must apply. In a demographic context this means that the population at the beginning of a time period is equal to the population at the end plus all the births in that time period, plus the net in-migration minus the number of deaths. Clearly, the more sectoral and spatial disaggregation that is encountered, the more complex these accounting relationships become and we shall in due course describe alternative strategies based on master equations and micro-simulation for handling this complexity.

It is often useful to view accounting methods and modelling as distinct though complementary approaches. In some cases, for example multi-regional demographic accounts, forecasts of the future state of a system are derived purely from account-based methods. More often, though, in dynamic urban modelling we will be concerned with using both approaches in an integrated framework. In this way the accounts-based component will provide inputs into a variety of sub-models and, in turn, the outputs from these models will be incorporated into the set of accounts. We outline a strategy for doing this in section 8 of the paper.

One interesting and important area of debate, which is particularly relevant in the context of this paper, concerns the issue of whether to construct accounting systems at the macro- or micro- level. Traditionally, of course, most accounts have used an aggregate approach. These can be criticised on a number of levels. First, on the issue of representing complex systems, especially where there is considerable heterogeneity amongst the actors that in total constitute that system. In this situation, aggregate representations become cumbersome, inefficient and impose excessive demands on computer storage. Secondly, they can be inflexible in relation to the prior level of aggregation that has been chosen. It is a trivial task to aggregate upwards, but a very difficult task to disaggregate information from aggregate accounts. Thirdly, an aggregate approach restricts the user to categorised variables as opposed to continuous variables, and the latter may be of relevance when studies of, say, income and expenditure distributions are required.

As an alternative, a micro-level approach to accounting has a number of advantages, but also a number of drawbacks. It does, in principle, allow for an efficient representation of a complex and interdependent system. This argument in favour of a micro-approach, however, is not as pervasive as it may initially seem, and attention must be focused on the nature of the interdependency between system attributes (see Clarke and Williams, 1985, for a detailed discussion of this point). It has also been pointed out (Caldwell, 1981) that it is possible to embed life history information into micro-level representations of households and individuals. This allows for the introduction of Markovian effects into transition rate analysis; these are typically ignored in conventional accounting procedures. How important this proves to be will be dependent on the given application area. Suffice to say that the more complex the processes being studied, the more relevant life-history effects will be.

The least persuasive but often quoted argument in favour of a micro-level approach to accounting is that micro-level observations provide the basis for understanding change in a socio-economic system. This may well be the case in some instances but is not necessarily true in all cases. What demands careful consideration is the nature of the phenomena being studied, the type of questions posed for the modeller and the type of answers being sought.

Objections to using a micro-level approach often centre around data availability and computational processing requirements. In the first case it is generally true that a data set specified at the level of the individual units containing the appropriate attribute set will not be available for the application or spatial system being considered. There are a number of ways to overcome this hurdle. The most obvious but usually the most impractical and expensive solution is to carry out a sample survey. The second approach is to merge micro-data files from different sources. This is an approach extensively adopted in the USA in transfer-income studies (Ruggles, et al 1977, US Department of Commerce, 1980) but it is probably less appropriate at the urban or regional scale. Thirdly, the use of synthetic sampling methods to generate micro-data from known aggregate distributions is another possibility. These methods use iterative proportional-fitting techniques to generate full, joint distributions of attributes from known marginals. Monte Carlo methods are then used to sample from this joint distribution to generate hypothetical individuals and households (see Clarke, 1985, for an example) in a consistent form.

The processing of long lists of household and individual attributes can be demanding in terms of computing resources, but this argument is likely to be of dwindling relevance as rapid advances are made in processing power. In any case, the processing time of a micro-data accounting system should be compared with the storage and memory requirements of the equivalent aggregate approach.

Another disadvantage of micro-based approaches relates to what has been termed the 'fallacy of composition'. This refers to the problem that in some cases the response of a population in aggregate will not correspond to an aggregation of the individual responses obtained from a micro-model. This presumably arises from the fact that the response to certain situations is mediated by aggregate level variables (unemployment rates, prices, etc) that need to be estimated prior to the determination of a response. In other words this is the old-fashioned aggregation problem making a re-appearance. Our response to this issue is that it is quite clearly a problem of model design and the solution will necessitate the use of mixed macro- and micro- methods and an approach is outlined in section 7.

To conclude this section, we argue that a flexible approach to accounting be adopted. The merits of both aggregate and micro- approaches to accounting should be examined in the context of the particular application being studied. In almost any situation it will in principle be possible to construct accounting schemes based on either approach (and we note that by definition they should give the same results). What we advocate in the context of a comprehensive dynamic urban model is a mixture of approaches and these are described in section 7 below.

4. Approaches to ~~and~~ methods for building dynamic models

We assume for the purposes of the present exercise that we are given the changing aggregate population and economic backcloths. In the population case, suitable account-based models are available (as mentioned in the previous section, cf. Rees and Wilson, 1977) provided suitable assumptions are made about transition rates. The economic case is more difficult. There are dynamic input-output models, but the complexities of the modern international economy are great and this makes forecasting very difficult. In practice, some more ad hoc approach probably has to be adopted: making exogenous assumptions which can be modified as new information becomes available.

For the remaining subsystems, it is perhaps helpful to think of there being two issues to be dealt with at the outset in each case: an indication of the speed of change, and a specification of the mechanisms of the process of change. The simplest assumptions are that the speed is very fast and that, following a change in some 'leading' parameter or variable (perhaps from another submodel) the mechanism of change is that the system should move to a new equilibrium in a process governed (say) by profit maximisation and competition. This leads to a standard comparative static model. These assumptions are usually applied to, and are reasonable for, most of the population allocation models: the standard spatial-interaction-based models of service usage, for instance, are of this type. So also are the models of change of (say) retail activity levels (cf. Harris and Wilson, 1978, Wilson and Clarke, 1979, Clarke and Wilson, 1983) when coupled with comparative static assumptions. There is an important difference between the two cases, however: in most of the population examples, change is smooth; in most of the rest, 'discrete' structural change is possible and the ideas of catastrophe theory and bifurcation theory come into play (cf. Wilson, 1981-A).

The retail model can be used to show how these ideas can be generalised to cope with speeds of change which are slower than what is needed to make comparative static assumptions appropriate. Let $D_j(W_j)$ be the revenue attracted to zone j in a retail system when the activity level at j is W_j. Let $C_j(W_j)$ be the cost of supplying this facility. Then, if comparative static assumptions apply, the process which describes the equilibrium is

$$D_j(W_j) = C_j(W_j) \tag{1}$$

If the system is not in equilibrium, however, the dynamics can be described by (say)

$$\dot{W}_j = \varepsilon[D_j(W_j) - C_j(W_j)] \tag{2}$$

and now ε is a constant which measures the speed of change - the higher the ε value, the faster the rate of change, and in this case, the faster the return to equilibrium. Dynamical systems of this kind have interesting bifurcation properties in terms of εD_j (cf. May, 1976, Wilson, 1981-B) but the details of this need not concern us here.

Two features of this kind of dynamics are particularly important in comprehensive model building. First, there will typically be many different speeds $\varepsilon_1, \varepsilon_2, \varepsilon_3, \ldots$ in different submodels, and this will lead to particular complexities because of the interactions between the submodels. Secondly, the mechanism can be extended to be applied to prices (p_j, say) and land rents (r_j, say), so that (2) becomes:

$$\dot{W}_j = \varepsilon^{(w)}[D_j(W_j) - C_j(W_j)] \quad (3)$$

$$\dot{p}_j = \varepsilon^{(p)}[D_j(W_j) - C_j(W_j)] \quad (4)$$

$$\dot{r}_j = \varepsilon^{(r)}[D_j(W_j) - C_j(W_j)] \quad (5)$$

$\varepsilon^{(w)}$, $\varepsilon^{(p)}$, and $\varepsilon^{(r)}$ still represent different speeds of adjustment, but now also can be interpreted as the relative power of the different kinds of <u>agents</u> involved in the processes of adjustment (developers, retailers and landlords in this case). Thus the articulation of the dynamic model structure is intimately linked to the specification of the underlying hypotheses (cf. Wilson, 1985-A). This way of looking at dynamic models enables us to discriminate in quite an interesting way between different approaches. Suppose from time t to time $t + \Delta t$, a parameter or exogenous variable changes for a system such as that represented by (3)-(5) above. We consider three of seven possible permutations of ways of handling the solution to represent different model hypotheses.

(i) Comparative statics. At <u>both</u> t and $t + \Delta t$, solve each of (3), (4) and (5) iteratively which will produce equilibrium states for $\{W_j\}$, $\{p_j\}$ and $\{r_j\}$, provided each of the ε's is sufficiently small. The relative size of the ε's will have an influence on the solutions through the mechanism discussed earlier.

(ii) The typical neo-classical economic model. At both t and $t + \Delta t$ solve (4) and (5) to bring the whole system into equilibrium in each case through price and rent adjustments. If there is an exogenous change between t and $t + \Delta t$, adjust W_j through a single step according to (3) so that the stock quantities move in the direction of equilibrium; but only at $t + \Delta t$ is the whole system faced into equilibrium through the price-rent mechanism.

(iii) Continual disequilibrium and incremental change. This is the other extreme to (i): when the exogenous change takes place during the period, adjust each of W_j, p_j and r_j by one step according to

(3)-(5). If there are no further exogenous changes, and the ε's are sufficiently small, the system will eventually reach an equilibrium state. If exogenous changes continue, then the system will never reach equilibrium but each incremental step will be influenced by any underlying equilibria.

These three cases are shown diagrammatically in Figure 9. The argument has been presented for the retail/service subsystem, and we have shown there are potential complexities within that system as a consequence of the different possible effects. (And for that subsystem, the particular model, say of (i)-(iii) to be adopted is a matter ultimately of empirical testing). However, a similar argument applies for other subsystems: housing (cf. Clarke and Wilson, 1983-B), industrial location (cf. Birkin and Wilson, 1985-A, 1985-B) and agriculture (cf. Wilson and Birkin, 1985). We have also drawn the land subsystem fairly directly into the comprehensive portrait by using land rents, as in (5) above. In practice, we would have to relate (5) directly to other subsystems to represent the competition for land as a fixed resource. The rent model would have to be something like

$$\dot{r}_j = \varepsilon^{(r)} \underset{k}{\mathrm{Max}}[D_j^k - C_j^k] \tag{6}$$

where D_j^k and C_j^k are the equivalents of $D_j(W_j)$ and $C_j(W_j)$ for alternative subsystems, k. The effect of (6) would be to incorporate a mechanism which allocated land use through a process which maximised bid rent. In this case in particular, the incremental model (iii) would be better than the other two alternatives, particularly for stock and land use adjustment, because it would then be possible to take inertia into account and to modify W_j (or its equivalents) so that decrease can only take place at a certain rate. (There are of course remaining complications to be dealt with, like the conversion of existing buildings for new uses).

It is useful to summarise the position reached so far before proceeding to incorporate the loosely-defined system of submodels presented above into a broader conceptual framework. Dynamic subsystem models can be defined. In each case, detailed mechanisms of change have to be hypothesised in relation to the ε-parameters and the way they are calculated. They are interdependent through common components, particularly the population, and in the competition for land and the determination of land rents. A rich variety of bifurcations can be expected, both within subsystems and also through the linking components, because the endogenous variables of one subsystem are among the 'parameters' of other subsystems. Finally, although the methods can in principle be applied to all the subsystems of Figure 1, as we have largely indicated, it should be emphasised that the industrial subsystem in particular needs much more research and the representation of deeper levels of complexity (perhaps through 'configuration analysis' - cf. Wilson, 1985-B); and the transport system is difficult on the network supply side (cf. Wilson, 1983-).

We can now proceed to the last steps of the argument on methods for dynamic model building. As we have noted earlier, the accounting basis we seek essentially provides the conservation equations of the system: nothing is 'lost'; all aspects of change are explicit in relation to the real entities of the system. It also provides the basis of two further aspects of dynamic comprehensive modelling: by keeping track of entities, it ensures that subsystems are correctly linked (through their common components and the ways they are changing); and secondly, a systematic account of change provides the means of calculating transition rates per unit time. These represent a more direct manifestation of the ε-coefficients which appeared in our earlier illustrations above. It is at this point, therefore, that we can seek new frameworks within which dynamic comprehensive models can be embedded, based on accounts and transition rates per unit time. There are two contributions under this heading. The first is the micro-simulation methodology, which allows us to handle a large number of entity subscripts simultaneously and still to handle change. The second is the master equations' framework which enables the overall accounting system within a structure which recognises the probabilistic nature of forecasting. The micro-simulation method is still relevant within the master equations' framework because it provides a means of solving the equations. Micro-simulation is the subject of the next section. Here, therefore, we briefly round off this section with a sketch of the relevance of master equations to dynamic comprehensive modelling.

The master equation method (cf. Weidlich and Haag, 1983; Haag and Wilson, 1985) essentially involves characterising the system state $\underline{x}$ and the whole set of 'nearby' states $\underline{x}'$, say, each of which differs from $\underline{x}$ in the state of one entity. $\overline{w}^{(+)}(\underline{x}', \underline{x})$ is the transition rate per unit time from $\underline{x}'$ into $\underline{x}$, $w^{(-)}(\underline{x}, \underline{x}')$ that for movement out of $\underline{x}$ to an 'adjacent' state $\underline{x}'$. At time t, the whole system is characterised by a probability distribution $P(\underline{x}, t)$. The master equation then specifies the rate of change of this as

$$\frac{\partial P(\underline{x}, t)}{\partial t} = \sum_{\underline{x}'} w^{(+)} (\underline{x}', \underline{x}) P(\underline{x}', t) - \sum_{\underline{x}'} w^{(-)} (\underline{x}, \underline{x}') P(\underline{x}, t) \tag{7}$$

This is a powerful general representation. It is difficult to handle in exactly this form because for a large complex system, the vector $\underline{x}$ has a very large number of elements and it is impracticable to keep track of $P(\underline{x}, t)$ as it 'fans out' from some initial state $\underline{x}^{(0)}$ for which $P(\underline{x}^{(0)}, 0) = 1$. In practice, therefore, it is usually necessary to use the mean value equations. However, micro-simulation can help to retain some stochastic features in a model framework of this kind, as we will see in the next section. In applications, it is the transition coefficients $w^{(+)}$ and $w^{(-)}$ which have to be related to the accounting base. If there is a theory, however, as with equations (3)-(5), this can be used as a basis for the specification of the w-rates. In Haag and Wilson (1985), for example, it is shown that if the w's are made constructed as an appropriate function of $D_j - C_j$, then the results of the model (3)-(5) can be exactly reproduced. (In this case, though this has yet to be tested, the same bifurcation effects should show themselves, but as a result of a different kind of calculation).

5. Micro-simulation methods

Until the late 1950's the vast majority of operational models in economics and regional science were constructed at the aggregate level. This was mirrored in urban modelling where attempts to consider the complexity and interdependence of urban systems were effected through the disaggregation of aggregate models as opposed to an explicit micro-level representation. Only recently has this situation changed.

The main thrust for the development of an alternative approach to modelling economic systems came about as a response to dissatisfaction felt towards the conventional approaches of say Tinbergen (1939) on business cycles and Leontief's (1951) input-output framework. This dissatisfaction arose out of the failure of aggregate approaches to capture the heterogenity and interdependence that can be found amongst and between the various components in an economic system as well as the insensitivity of many aggregate models to policy issues, particularly in the analysis of response to policy.

Guy Orcutt and his colleagues, working firstly at the University of Wisconsin (Orcutt et al, 1961) and later at the Urban Institute in Washington (Orcutt et al, 1976) were the first to build models of an economic system specified at the level of the individual decision-making unit. Although they had other ambitions the main output of their work consisted of a number of models (notably DYNASIM) that addressed the changing economic activity of households and individuals in response to a variety of transfer-income programs.

The justification for the adoption of a micro-level approach has been briefly mentioned in section 3. These relate to issues of representation of complex systems, a recognition of the interdependence at the micro-level between individual attributes and events, as well as a concern with distributional issues in policy analysis. A full description of these factors can be found in Clarke and Williams (1985) and in this section of the paper we restrict ourselves to highlighting the principle features, attractions and drawbacks of using micro-models particularly in relation to the construction of dynamic comprehensive models. Although there now exists a considerable body of literature on the use of micro-simulation models (e.g. Havemaan and Hollenbeck, 1980, Caldwell, 1982, 1985, Bungers, 1981, Merz and Quinke, 1985) there would appear to be lacking a simple outline of the range of models that have been developed and their common features. We therefore regard a rectification of this situation a subsidiary aim of this section.

There are two main stages involved in the development of micro-simulation models. First a data base, consisting of a suitably specified population of actors, must be assembled. The actors may be individuals, households, firms, banks, or whatever, depending on the application. The second stage involves processing this population through a set of rules that will in some way change a variety of the individual members' attributes. We discuss each of these stages in turn.

The specification of an initial population can be undertaken in a number of different ways, as outlined in section 3. To recap these involve obtaining survey data, the merging of two or more micro -data files to produce a relevant attribute list or synthetic sampling to create micro-data from aggregate distributions. In most cases only a sample of a population will be required. The size of this sample will be determined by the variability amongst and between the attributes being considered. The second stage, the updating of the characteristics of the sample population can take a number of forms. At least four different but in some senses related methods can be identified. The first is a purely static approach, the other three all involve an attempt to consider dynamics.

Static approaches tend to examine how a change in a rule-based-system will affect the characteristics of a population. A good example of this is TRIM (Transfer of Income Model, Sulvetta, 1978) used by the United States Congress to analyse the budgetory and distributional consequences of planned transfer programs. In this case the analyst is interested in the 'before' and 'after' consequences of some policy proposal. This can be examined by changing the rules, say for eligibility of benefits and the income bands for different levels of taxation. Usually there is no attempt to examine the larger term impacts of the planned changes.

Once attention is shifted towards an interest in dynamics then a whole set of modelling issues arise. Much is often claimed for micro-level approaches to dynamics and it is therefore appropriate to clarify the purposes of adopting this approach. As a general rule the analyst is not interested in the fate of individual households in a population but in aggregate outcomes. The aim of most dynamic models is to solve a set of linked differential or difference equations which take the general form

$$\underline{X}_{it+1} = \underline{X}_{it} + \sum_{j\neq i} (\underline{X}_{jt}\, p_{jit+1}) - \sum_{j\neq i} (\underline{X}_{it}\, p_{ijt+1}) \qquad (8)$$

where $\underline{X}_i$ represents the vector of attributes associated with a particular state i, for example the number of single persons who live in furnished rented accommodation. In other words the value that a particular cell in an occupancy matrix takes at time $t + 1$ is equal to the value at t plus the new entrants to that state minus the leavers. p_{ji} and p_{ij} are transition rates for movements between different states . Micro-simulation can be seen as one way of solving these dynamic equations. The major modelling task, of course, is the specification of the transition rates (ρ_{ij}) and it is when there is interdependency and complexity in this specification that micro-simulation methods will be particularly useful.

Returning to the three methods of approaching dynamics we can note that they all attempt in different ways to produce estimates of $\underline{X}_{it+1}$. The first method is known as static ageing (Bungers, 1981) and is used when only small changes are expected in the future population. In this case the initial population is adjusted in such a way as to match expected aggregate distributions. No formal account is taken of the processes that generate this change. The second and third approaches both treat dynamics explicitly through the use of list processing. This involves examining the characteristics of each individual and household in the sample population, determining, on the basis of their attributes, which transitions they are eligible for and, through the use of conditional probabilities, using Monte Carlo sampling to determine if they are deemed to undergoe that transition. An advantage of the approach is that the second-order effects of a transition can be readily handled. For example if a female is deemed to give birth she can be removed from the labour market, her income will change, the household income will change, the household size will change and the eligibility for a variety of social welfare benefits will also change. Dealing with these effects at the level of the individual ensures consistency in relation to the accounting principles we outlined in section 3.

The determination of the conditional probability distributions is, of course, central to the micro-simulation approach. It can be achieved in two ways and it is this that distinguishes the final two approaches. One way is to use aggregate look-up tables that have been obtained from official publications, or as an alternative generated from an aggregate model. The second is to estimate a set of appropriate parameters of behavioural relationships from micro-level data. This, for example was the approach adopted by Orcutt et al (1976) in their DYNASIM model. A pre-requisite for this is the presence of a micro-data set, and in many cases this will simply not be available.

There are, of course, a range of technical problems associated with these models and we refer the reader to Clarke and Williams (1985) for a full discussion of these. We would like to focus just on one area - the relationship between macro- and micro- approaches. For some dynamic processes it will be satisfactory to assume that the 'aggregate economic environment' is not influenced, at least not directly, by individual transitions. Mortality would be a good example of this. However there are other processes where an explicit recognition of the interdependency between micro- and macro- level processes is necessary. For example, in both the labour and housing systems potential movers are at the same time both demanders (seeking new job or house) and suppliers (vacating job or house). In this situation it will be appropriate to aggregate over various supply and demand categories and solve some equilibrium allocation model. The resulting allocation and associated output (prices, wages) can then be converted into corresponding transition rates and fed back into the micro-model. This approach will be most useful when we consider a number of different but inter-related subsystems in the comprehensive model which we describe in section 7.

To give a little flavour of the approach we now briefly describe an example of how we have used the micro-simulation methodology in practice. The example relates to household forecasting at the Regional level, in this case for Yorkshire and Humberside. A full account of the application can be found in Clarke (1985). The list processing exercise considers the following demographic processes: birth, death, marriage, divorce and migration. Each of these events may have important knock-on effects as we have already noted. In Figure 10 we outline, in diagrammatic form, the structure of the model we have developed. Each individual in the sample population is tested for each transition he or she is eligible for. The relevant conditional probabilities are obtained from regional data obtained or modified from the Registrar General's estimates. As can be readily detected there is a considerable amount of interdependence to be found in the processes that operate at the micro-level. It would be impractical to account for these in a consistent manner if an aggregate approach was adopted, simply due to the size and complexity of the appropriate transition matrix. In adopting a micro-approach however we are forced to make certain assumptions that may result in some errors being introduced. For example the list processing methodology implies a sequential as opposed to simultaneous approach to treating transitions. This means that the ordering of events may influence the nature of the results obtained. For example if an individual is tested for death before giving birth this could exclude the possibility of a birth before death. Methods for overcoming these problems do exist but they can add substantially to the processing time.

6. Model use and indicators of system performance

Typical uses of urban models have involved forecasts of the variables directly generated in the model within a largely physical planning process. Exceptions to this have been the calculation of consumers' surplus associated with transport system changes (Foster and Beesley, 1963, Wilson and Kirwan 1969, Williams, 1977 for example) and the use of various accessibility indices (see G P Clarke and Wilson, 1985, which includes a review of this literature). Benefit measurement using consumers' surplus has been extended to incorporate the effects of facility size in services like retailing (Wilson, 1974, p.363). What is now needed is a considerable further extension of these ideas to develop whole batteries of performance indicators. This task is reviewed broadly by G P Clarke and Wilson (1985); the ideas presented have received considerable stimulus from the development of performance indicators in the health service - as reviewed in Clarke and Wilson (1984-). We take the argument in three stages. First, we outline some basic geographical ideas about the nature of the relevant performance indicators. Secondly, we examine the obvious range of application. Thirdly, we discuss how to use the dynamic comprehensive modelling framework to progress towards greater realism and to deal with more difficult issues.

Let us start with the broad view that an urban region exists to 'serve' its inhabitants in some way and that the task of any kind of planning is to improve this service, particularly for those sections of the community who are poorly served in various ways. This, of course, is a naive view of 'purpose' and the nature of cities, and indeed of planning, but is is a useful hypothetical starting point which can be appropriately qualified later. Consider Figure 11. This shows that most 'services' (even including, say, the supply of jobs in the labour market) involve travel, and this is inter-zonal flow in our representation of a city. There are thus two kinds of foci for performance: residential zones and their population; and service-providing zones. There are correspondingly two types of indicators: those which measure the <u>effectiveness</u> of what is on offer to residents; and those which measure the <u>efficiency</u> of what is supplied from service zones. To calculate the first, it is necessary to 'channel back' via the interaction matrices take up from service zones to residential zones; and for the second, to calculate a catchment population. Then it is possible to calculate take up per head of residential population as an effectiveness indicator and provision per head of catchment population in service zones. A good example is now being provided by one of the first-line indicators being recommended by D.H.S.S. (1985) in health services planning. Take acute hospital expenditure by service zone. Use a patient flow interaction model to estimate the amounts spent on patients by residence (treated anywhere) and the catchment populations of service zones. It is then possible to examine the spatial distributions of expenditure on residents per head of residential population, and expenditure on services per head of catchment population, and the results are very interesting.

The second stage of the argument is to note that this kind of method can be used in relation to most of the subsystems of a comprehensive model, though sometimes, modifications are needed. In the case of the labour market, for instance, we can examine the effectiveness and efficiency of urban spatial organisation as suppliers of jobs to the population. The housing market is more complicated because it is only indirectly interaction-based. And this leads to the third point: we need to extend the conceptual base of comprehensive models to link performance indicators from what seem at first sight different groups. For example, it is largely income derived from employment which facilitates the consumption of housing in different areas. The micro-simulation formulation in particular enables us to maintain linkages of this kind.

7. The assembly of comprehensive model systems: principles and examples

It is clear, if implicit, in the argument so far that it is impossible to recommend a single design for a comprehensive model. It is necessary to select the elements from the tools available which will allow an effective model to be constructed to meet any particular circumstances. We begin, therefore, by summarising the elements available and developing examples which show how different models can be built. The common feature in each case is the existence of an (implicit or explicit) set of accounts which provides the threads which stitch the submodels together.

The three main groups of methods which have been identified can be summarised as follows:

A. SIA-TA systems: spatial-interaction-activity models with some time adjustment mechanism added.

B. ME-MVE systems: master equation/mean value equation models.

C. MS: micro-simulation models.

We have established that there is more in common between these approaches than may be evident at first sight. The main similarities relate to the mechanisms of transition: adjustment mechanisms (A); transition rates per unit time (B); probability distributions and transition probabilities (C). Each of these would involve 'constants' or rates which are, in effect, measured from an account of historical change of the elements of the real system. It should be possible to make these connections explicit. It then becomes clear that the differences are matters of technique which arise from such consideration as levels of resolution and the degree of explicitness adopted in the way the transitions are represented. At the coarser scales, A-techniques are the most convenient and have the added advantage that analyses of equilibrium states can be provided which offer great insights into the structures and trends at any one time. At a very fine scale, C-techniques are necessary because this is the only way to handle the large number of characteristics involved. The B-system is in one way nearer to the A-system in usual resolution but it provides at least three potential advantages: (i) an ability to work with changing probability distributions explicitly, rather than means; (ii) the capability of explicit modelling of all the transitions when the system is initially in disequilibrium and continues to be; and (iii) parameter estimation procedures which can be applied to data for systems not in equilibrium. However, both A- and B-systems can be conceived at finer levels of resolution, and then, with appropriate definitions, they are transposed into C-systems for computational purposes. Indeed, it is possible to see C-system equations explicitly as M.V. equations with an M.E. foundation.

In order to decide which are the most useful examples of comprehensive models to pursue, it is appropriate to make a broad brush distinction between submodels concerned with the population and associated activities on the one hand and organisation ('the economy') and economic activities on the other. Then some obvious combination of methods are shown on Table 1 - though there are others, including subdivisions within the population and economic categories.

Table 1

	Pop.	Econ.	
Example 1	A	A	
Example 2	B	B	(or exogenous)
Example 3	C	A	
Example 4	C	C	

Example 1 is the 'conventional' comprehensive model - a 'Lowry-type' model extended to incorporate dynamic submodels relating to both population and the economy. The economic part can in principle be extended to include manufacturing industry and agriculture (cf. Birkin and Wilson, 1985-A, 1985-B; Wilson and Birkin, 1985-A). However, we do not pursue this here. One example, which includes the results of numerical experiments, is presented in Birkin, Clarke and Wilson (1984). It should be emphasised that this approach remains interesting for many problems, particularly in providing an overall 'backcloth' for finer-scale (possibly subsystem-based work). Example 4 is also interesting but involves research issues which are beyond the scope of this paper in the development of micro-simulation techniques to organisations in the economy. So we leave that on the research agenda and focus on examples 2 and 3 which we pursue in turn below.

Example: the master equation approach

In this illustration, we choose the simplest example which will demonstrate the application of the master equation methodology to both population activity and economic activity. This example relates to choice of services by the population, the supply of those services by those sectors of the economy and the influence of competition for sites on land rent. Although this is a limited example in the context of comprehensive model building, it is easily extendable. For the example, we follow the skeleton of the argument in Haag and Wilson (1985): for extensions, see Weidlich and Haag (1983) and Haag (1985-A, B, C). For simplicity, we consider a simple aggregate service sector, but disaggregation is straightforward.

Let $\underline{T}$ be the matrix T_{ij}, the level of useage of the service facility at j by the residents of i; let $\underline{Z} = \{Z_j\}$, with Z_j as the scale of provision at j; let $\underline{p} = \{p_j\}$ be the prices at j and

$\underline{r} = \{r_j\}$ the rents. Then let $P(\underline{T}, Z, \underline{p}, \underline{r}, t)$ be the probability that the system is in state $\{\underline{T}, \underline{Z}, \underline{p}, \underline{r}\}$ at time t. For ease of illustration, we assume that this can be factorised, using an obvious notation, as

$$P(\underline{T}, \underline{Z}, \underline{p}, \underline{r}, t) = P^{(1)}(\underline{T}, t)\, P^{(2)}(\underline{Z}, t)\, P^{(3)}(\underline{P}, t)\, P^{(4)}(\underline{r}, t) \tag{9}$$

We begin with destination choice dynamics. Let $\underline{T}(ij_-, ik_+, t)$ denote the configuration

$$\{T_{11}, T_{12}, \ldots T_{ij}-1, \ldots T_{ik}+1, \ldots\} \tag{10}$$

That is, it differs from $\underline{T}$ by a shift of one unit from j to k by a resident of i. The methodology is based on the specification of transition rates from state $\underline{T}$ to state $\underline{T}(ij_-, ik_+)$, that is to 'nearby' states defined in this way. These rates have to be defined for all i, j and k. Thus, let $\pi^i_{jk}\,[\underline{T}(t), \underline{T}(ij_{-1}, ik_{+1}, t)]$ be that transition rates per unit time. Then if $E_i(t)$ is total service usage by residents of i, the total transition rate is

$$w^{(1)i}_{jk}\,[\underline{T}(t)] = E_i(t)\,\pi^i_{jk} \tag{11}$$

The master equation then specifies the rate of change of the configuration probability P in terms of these rates (cf. equation (7) in Section 4 above):

$$\frac{\partial P^{(1)}(\underline{T},t)}{\partial t} = \sum_{ijk} w^{(1)i}_{kj}\,[\underline{T}(ij_{-1}, ik_{+1}, t)]\,P^{(1)}(\underline{T}(ij_{+1}, ik_{-1}, t) - \sum_{ijk} w^{(1)i}_{jk}\,[\underline{T}(t)]\,P^{(1)}(\underline{T}(t)) \tag{12}$$

Intuitively, the change in $P(\underline{T}(t))$ is made up of the difference between all the ways of making a transition into $\underline{T}(t)$ from states and all the ways of moving from $\underline{T}(t)$ to nearby states.

It should be emphasised that (12) is a very rich representation of the system at each time t. It is possible to calculate from it, given initial conditions, not only the most probable state at each future time (as say with entropy maximising methods) but the probability of <u>any</u> configuration occurring at <u>any</u> time. In practice, of course, the computation of this makes an enormous demand on computer storage and for this reason, it is usually necessary to work with the mean-value equations. These can be obtained by multiplying the left and right hand sides of (12) by T_{ij} and summing over all possible configurations $\underline{T}$ to give

$$\frac{d\bar{T}_{ij}}{dt} = \sum_k W^{(1)i}_{kj} \bar{T}_{ik}(t) - \sum_k W^{(1)i}_{jk} \bar{T}_{ij}(t) \tag{13}$$

and these equations are much more manageable. They also give equations for the equilibrium state:

$$\sum_k W^{(1)i}_{kj} \; T_{ik}(t) = \sum_k W^{(1)i}_{jk} \; T_{ij}(t) \tag{14}$$

A similar argument can be carried through for the providers of services in relation to $\underline{Z}(t)$ and for prices $\underline{P}(t)$ and rents $\underline{r}(t)$. In these cases, however, instead of seeing the underlying process as a 'migration' - the shift of custom from j to k - it is more appropriate to think of provision and change as a birth-death process. For $P^{(2)}(\underline{Z}, t)$, for example, the transition rates are $W^{(2)+}_j$ and $W^{(2)-}_j$, the rates at which a unit of service provision is increased or decreased at j. Then the appropriate master equation is

$$\begin{aligned}\frac{dP^{(2)}}{dt}(\underline{Z}, t) = & \sum_j W^{(2)+}_j [\underline{Z}(j_{-1}), t] \, P^{(2)} [\underline{Z}(j_{-1}), t] \\ & - \sum_j W^{(2)-}_j [\underline{Z}, t] \, P^{(2)} [\underline{Z}, t] \\ & - \sum_j W^{(2)+}_j [\underline{Z}, t] \, P^{(2)} [\underline{Z}, t] \\ & + \sum_j W^{(2)-}_j [\underline{Z}(j_{+1}), t] \, P^{(2)} [\underline{Z}(j_{+1}), t]\end{aligned} \tag{15}$$

Similar equations can be provided for $P^{(3)}(\underline{P}, t)$ and $P^{(4)}(\underline{r}, t)$, and there are corresponding mean value equations in each case.

It is clear that the crucial steps in the argument so far are the specification of the system state (together with the concept of nearby states) and the setting up of an appropriate master equation - mean value equation framework based on either 'migration' or 'birth-death' processes as appropriate (or a mixture). The final step is to add substantive hypotheses which determine the various transition rates. We now sketch the outlines of this final step for this example.

For population dynamics, consider

$$W_{jk}^{(1)i}\ [\underline{T}(t)] = E_i(t)\ \varepsilon^{(1)}(t)\ e^{v_{ik}(t) - v_{ij}(t)} \tag{16}$$

$E_i(t)$ is total population demand at i at t; $v_{ij}(t)$ is an estimate of the utility of using j (at t) for a resident of i. $\varepsilon^{(1)}(t)$ is a constant which scales the overall transition rate per unit time. Essentially, this is simply hypothesising that the rate at which people will switch their custom from j to k is a function of the difference in utilities of the alternatives. From the mean-value equation (13), we can calculate an estimate of the revenue attracted to j:

$$\bar{D}_j = \sum_i \bar{T}_{ij} \tag{17}$$

(and, if necessary, the rate of change). Suppose we also know the costs, $C_j[Z_j, t]$ of running a facility of scale Z_j at j at t. Then the behaviour of developers can be described by

$$W_j^{(2)+}(\underline{Z}, t) = \begin{cases} \tfrac{1}{2}\ \varepsilon^{(2)}(t)[D_j(\underline{Z}, \underline{p}, t) - C_j(\underline{Z}, \underline{r}, t)]Z_j(t), & \\ 0 \ \text{otherwise} & D_j > C_j \end{cases} \tag{18}$$

$$W_j^{(2)-}(Z, t) = \begin{cases} \tfrac{1}{2}\ \varepsilon^{(2)}(t)[C_j(\underline{Z}, \underline{r}, t) - D_j(\underline{Z}, \underline{p}, t)]Z_j(t), & \\ 0 \ \text{otherwise} & D_j < C_j \end{cases} \tag{19}$$

(where we now show D_j as a function of prices, $\underline{p}$, and C_j as a function of rents, $\underline{r}$). Similar hypotheses can be made for $W^{(3)}$ and $W^{(4)}$.

As a final step, we can make utility explicit by taking

$$2v_{ij}(t) = \alpha(t)\log Z_j(t) - \gamma(t)\ p_j(t) - \beta(t)c_{ij}(t) \tag{20}$$

(where $c_{ij}(t)$ is the cost of getting from i to j at time t).

The system is now fully specified. With a sufficiently large computer, it would be possible to model the time variation of the probability distributions explicitly. Otherwise, it is at least possible to work with the mean-value equations and to investigate equilibrium states. As noted earlier, it is also possible to provide calibration procedures which can be based on data relating to the system in disequilibrium. With this example, it is also possible to demonstrate the connection of this methodology with the SIA-TA approach to the same problem. If the substitutions are made for v_{ij} and the w's as hypothesised above into the master and mean-value equation, it is possible to reproduce exactly the results of Harris and Wilson (1978) and Wilson (1981-B, 1985-B) on this model in an alternative representation. It is also a reasonable conjecture that an equivalent micro-simulation procedure could be devised.

Example: micro-simulation

The third combination of approaches is that of using a mixture of aggregate dynamic models in conjunction with micro-simulation methods. This has been adopted for a retailing example in Clarke (1984) and described in a more general context in Birkin and Clarke (1985). The justification for using a mixture of methods centres around the need for a more detailed understanding of the demand side of the retailing system as well as being able to examine the distributional effects of alternative policies at the requisite level of disaggregation. The structure of the modelling framework that has been developed is shown in Figure 12. We start with a micro-level specified population of individual and household attributes. In a retailing context these will include employment, income and expenditure data. It is possible to generate the demand for a range of retail goods by zone by aggregating over the appropriate individual and household attributes. The aggregate demand generated in this way then forms the input into the retail supply models which take the form of those described in section 4. These supply models are then solved to produce a new size and distribution of retail facilities as well as associated prices. The next step is to determine how these changes in spatial structure, prices and so on influence the activities of individuals and households in the population. This can be achieved in a number of ways but generally involves converting aggregate distributions into probabilities which are then used to determine the shopping location of each household. The effects of changing prices may be examined by making changes to the household budget, along the lines suggested in Wilson and Pownall (1976). It is also possible to account for constraints on activities - for example, to ensure that no non-car owning households are allocated to out of town shopping centres. The final step in the cycle is to update the characteristics of the sample population, particularly to account for demographic, housing and employment change. This is achieved through list processing in the same way as we outlined in section 5. The updated population, with new retail demand characteristics is then the starting point in the next cycle of this framework.

An illustration of an attempt to construct the fourth example of a comprehensive model - constructed using purely C-type methods can be found outside of conventional regional science in the work of Bennett and Bergmann (1980). Their 'Transactions Model' has been designed to examine economic problems and policies in the USA. It consists entirely of decision-making and economic transactions simulated at the level of individual decision makers - separate firms, banks and institutions. While still at an experimental stage of development (although it has been fitted to time series data) the model proposes some interesting methods for short-term price and wage adjustments that may be of relevance to a more traditional urban and regional modelling approach.

8. Concluding comments: towards operational models

It is by now clear that it is impossible to recommend a particular design for a comprehensive model. However, a number of conclusions can be drawn from the argument presented and then we can set these against the issues to be considered in model design in any particular context. These conclusions can be summarised as follows:

(i) Comprehensive system specification. Even if the model which is ultimately built is partial, say for a labour market, it is useful to be aware explicitly of the form of its connections to the rest of the comprehensive model. This is clear from the diagrams of section 2.

(ii) Interdependence and accounts. The best way to represent interdependence in a consistent way is to define the algebraic variables in such a manner that they are the elements of a set of accounts. This is clear from sections 3 and 4.

(iii) There are at least three main available and relevant methods of analysis. They are relatively closely related. Each has advantages and disadvantages. They can be combined in different ways. The particular combination will be determined in relation to the kinds of issues to be discussed below. (Sections 4,5 and 7.)

(iv) It is possible to ensure that comprehensive models are more useful than they have been in the past by focusing on a wide range of performance indicators which can be calculated within an interactive planning framework. This integrates the activities of the analyst, designer and policy maker more closely than has been the case in the past. (Section 6)

We can therefore conclude by enumerating a check list of issues, the responses to which will determine the kind of comprehensive models to be built in different circumstances.

(i) Policy matters. It is important to begin by being as clear as possible about the policy issues of most concern. It is then possible to see what the different methodologies offer and to design an appropriate model system in relation to the more technical matters which follow.

(ii) Scale of analysis. What is the coarsest scale at which the policy issues can be effectively tackled?

(iii) Degree of closure/comprehensiveness. For the policy issues at hand, is it possible to build a relatively partial model?

(iv) Information availability. Will the data be available to make the model operational? Or can good estimates be made of missing data?

(v) Resources available. The above issues will determine the kind of model required. Are resources available - say skilled labour and computing power - to build such a model and operationalise it in a reasonable time. If not, return to step (i) and try another iteration!!

In summary: the broader the range of policy issues the more comprehensive the model should be. The more detail which is required, the finer the scale should be. The principles and examples of section 7 should then allow a model to be designed; but information and resource availabilities are likely to constrain ambition.

References

Bennett, R.L. and Bergmann, B.R. (1980) 'Policy explorations with the transactions of the US economy' in Havemann, R.H. and Kollenbeck, K. (eds.) *Microeconomic Simulation Models for Public Policy Analysis, vol. 2*, Academic Press, New York.

Birkin, M. and Clarke, M. (1985) Comprehensive models and efficient accounting framework for urban and regional systems, Working Paper, School of Geography, University of Leeds.

Birkin, M., Clarke, M. and Wilson, A.G. (1984) Interacting fields: comprehensive models for the dynamical analysis of urban spatial structure. Paper presented to the 80th Annual A.A.G. meeting, Washington DC, April 1984. Also Working Paper 385, School of Geography, University of Leeds.

Birkin, M. and Wilson, A.G. (1985-A) Industrial location theory I: a review of approaches in an integrated framework, Working Paper 400, School of Geography, University of Leeds.

Birkin, M. and Wilson, A.G. (1985-B) Industrial location theory II: application of concepts of dynamical systems theory, Working Paper 401, School of Geography, University of Leeds.

Bungers, D. (1981) Microanalytic simulation models as tools for legislative planning, *Simulation, 35*, pp. 111-118.

Caldwell, S.B. (1983) Modelling demographic economic interactions - micro, macro and linked micro-macro strategies, *Socio-Economic Planning Sciences, 17*, 5-6, pp. 365-372.

Caldwell, S.B. (1985) Recognising heterogeneous responses to policy, *Sociological Methods and Research, 13*, 3, pp. 387-405.

Clarke, G.D. and Wilson, A.G. (1985) Performance indicators within a model-based approach to urban planning, forthcoming Working Paper, School of Geography, University of Leeds.

Clarke, M. (1984) Integrating dynamic models of urban structure and activities: an application to urban retail systems, unpublished Ph.D. thesis, School of Geography, University of Leeds.

Clarke, M. (1985) 'Demographic processes and household dynamics: a micro-simulation approach' in Woods, S.R. and Rees, P.H. (eds.) *Developments in Spatial Demography*, Allen and Unwin, London.

Clarke, M. and Williams, H.C.W.L. (1985) *Micro-analysis in Urban and Regional Systems*, Cambridge University Press, Cambridge (forthcoming).

Clarke, M. and Wilson, A.G. (1983-A) The dynamics of urban spatial structure: progress and problems, *Journal of Regional Science, 21*, pp. 1-18.

Clarke, M. and Wilson, A.G. (1983-B) Exploring the dynamics of urban housing structure: a 56 parameter residential location and housing model, Working Paper 363, School of Geography, University of Leeds.

Clarke, M. and Wilson, A.G. (1984) Models for health care planning: the case of the Piemonte region, Working Paper 38, I.R.E.S., Turin, Italy.

Clarke, M. and Wilson, A.G. (1985) Health services planning with an interactive model system: preliminary results from a case study, Working Paper, I.R.E.S., Turin, Italy.

D.H.S.S. (1985) A Report of the Joint Group on Performance Indicators to the Secretary of State for Social Services, HMSO, London.

Foster, C.D. and Beesley, M.E. (1963) Estimating the social benefit of constructing an underground railway in London, *Journal of the Royal Statistical Society Series A, 126,* pp. 46-92.

Haag, G. (1985-A) Master equations, chapter 4 in Bertuglia, C.S., Leonardi, G. and Wilson, A.G. (eds.) *Modelling of urban dynamics,* forthcoming.

Haag, G. (1985-B) Housing market-2: a master equation approach, chapter 8 in Bertuglia, C.S., Leonardi, G. and Wilson, A.G. (eds.) *Modelling of urban dynamics,* forthcoming.

Haag, G. (1985-C) Services-2: a master equation approach, chapter 11 in Bertuglia, C.S., Leonardi, G. and Wilson, A.G. (eds.) *Modelling of urban dynamics,* forthcoming.

Haag, G. and Wilson, A.G. (1985) A dynamic service sector model: a master equations' approach with prices and land rents, Working Paper, forthcoming.

Harris, B. and Wilson, A.G. (1978) Equilibrium values and dynamics of attractiveness terms in productor-constrained spatial interaction models, *Environment and Planning, A, 10,* pp. 371-388.

Haveman, R.H. and Hollenbeck, K. (eds.) (1980) *Micro economic simulation models for public policy analysis, 1 and 2,* Academic Press, New York.

Leonardi, G. and Wilson, A.G. (1985) The elements for a comprehensive model, chapter 6 in Bertuglia, C.S., Leonardi, G. and Wilson, A.G. (eds.) *Modelling of urban dynamics,* forthcoming.

Leontief, W. (1931) *The Structure of the American Economy,* Oxford University Press, New York.

May, R.M. (1976) Simple mathematical models with very complicated dynamics, *Nature, 261,* pp. 459-467.

Merz, J. and Quinke, H. (eds.) (1985) *Microanalytic simulation models to support social and financial policy,* Elsevier, North Holland, New York.

Orcutt, G.H., Caldwell, S. and Wertheimer, R. (1976) Policy exploration through micro-simulation, The Urban Institute, Washington, D.C.

Orcutt, G.H., Greenberger, M., Rivlin, A. and Korbel, J. (1961) *Micro-analysis of socio-economic systems: a simulation study,* Harper and Row, New York.

Rees, P.H. and Wilson, A.G. (1977) *Spatial population analysis,* Edward Arnold, London.

Ruggles, N. (1977) Merging micro-data: rationale, practice and testing, *Annals of Economic and Social Measurement, 6, 4.*

Stone, R. (1971) *Demographic accounting and modelling,* OECD, Paris.

Sulvetta, M.B. (1976) *An analysts guide to TRIM - the Transfer Income Model,* The Urban Institute, Washington, D.C.

US Department of Commerce (1980) Report on exact and statistical matching techniques, Statistical Policy Working Paper 5, Washington, D.C.

Tinbergen, J. (1939) *Statistical testing of business cycle themes,* Society of Nations, Geneva.

Weidlich, W. and Haag, G. (1983) *Quantitative Sociology*, Springer-Verlag, Berlin.

Williams, H.C.W.L. (1977) On the formation of travel demand models and economic evaluation measures of user benefit, *Environment and Planning, A, 9*, pp. 285-344.

Wilson, A.G. (1974) *Urban and Regional Models in Geography and Planning*, J. Wiley, Chichester.

Wilson, A.G. (1981-A) *Catastrophe theory and bifurcation: applications to urban and regional systems*, Croom Helm, London.

Wilson, A.G. (1981-B) Some new sources of instability and oscillation in dynamic models of shopping centres and other urban structures, *Sistemi Urbani, 3*, 391-401.

Wilson, A.G. (1985-A) Structural dynamics and spatial analysis: from equilibrium balancing models to extended economic models for both perfect and imperfect markets, Working Paper 431, School of Geography, University of Leeds.

Wilson, A.G. (1985-B) Configurational analysis and urban and regional theory, Working Paper, forthcoming.

Wilson, A.G. and Birkin, M. (1985) Dynamical models of agricultural location in a spatial interaction framework, Working Paper 399, School of Geography, University of Leeds.

Wilson, A.G. and Clarke, M. (1979) Some illustrations of catastrophe theory applied to urban retailing structures, in Breheny, M. (ed.) *Developments in urban and regional analysis*, pp. 5-27, Pion, London.

Wilson, A.G. and Kirwan (1969) Measures of benefits in the evaluation of urban transport improvements, Working Paper 43, C.E.S., London.

Wilson, A.G. and Pownall, C. (1976) A new representation of the urban system for modelling and for the study of micro-level interdependence, *AREA, 8*, pp 146-254.

Figure 1

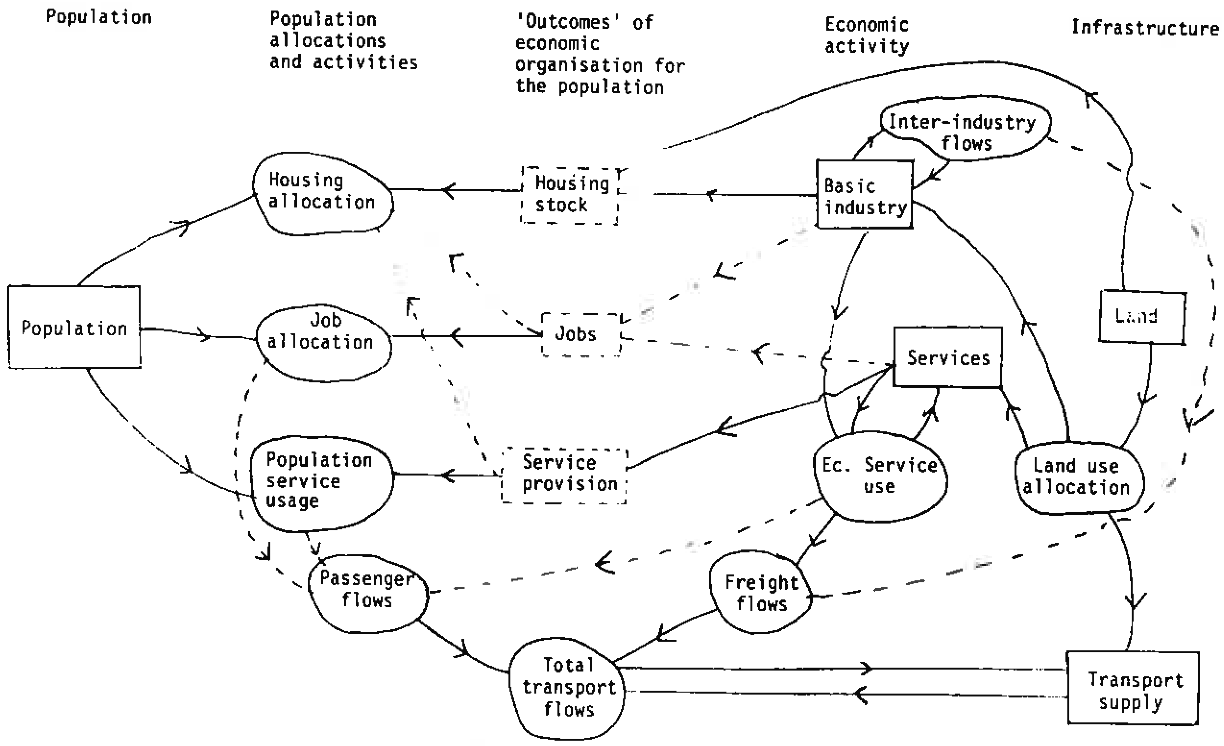

Population
Population allocations and activities
'Outcomes' of economic organisation for the population
Economic activity
Infrastructure
Population
Housing allocation
Job allocation
Population service usage
Passenger flows
Housing stock
Jobs
Service provision
Total transport flows
Basic industry
Inter-industry flows
Services
Ec. Service use
Freight flows
Land
Land use allocation
Transport supply

Figure 2. The housing market

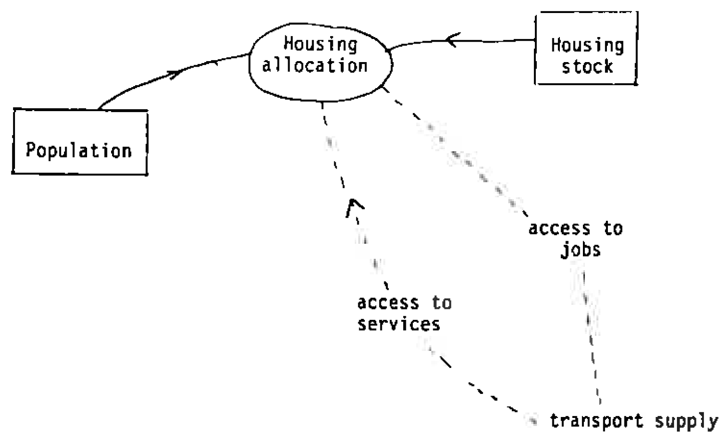


Figure 3. The labour market

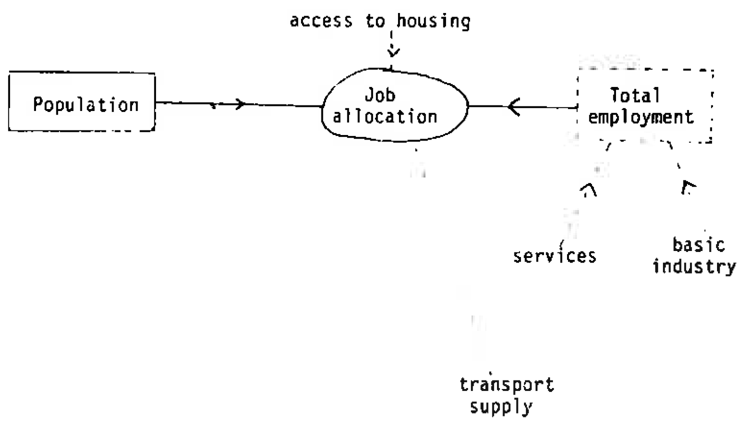


Figure 4. Industry and services

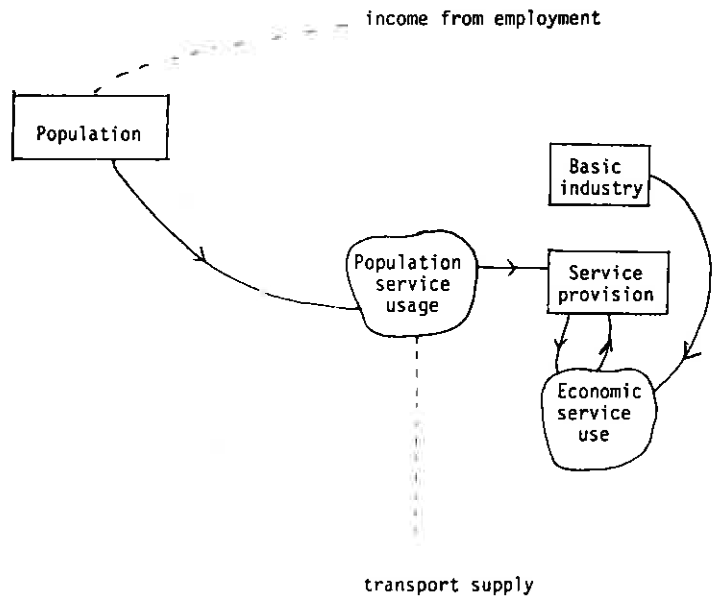


Figure 5. The land market

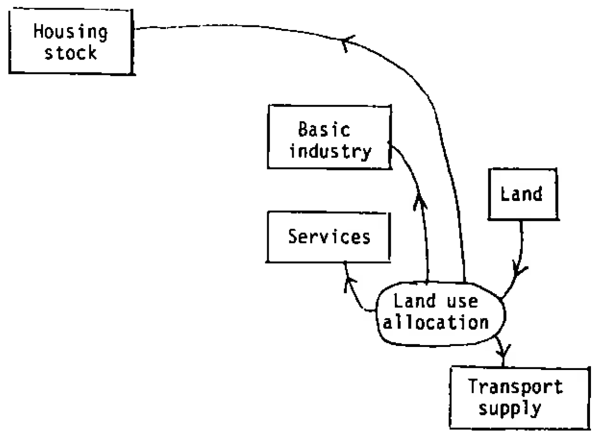
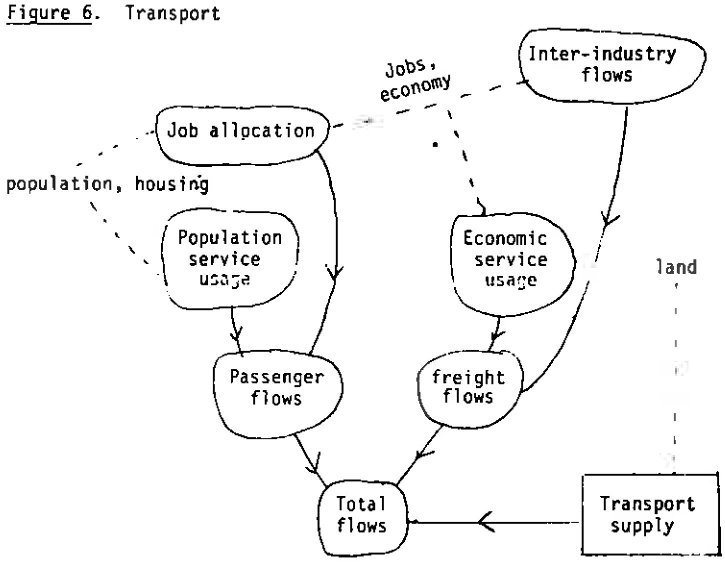


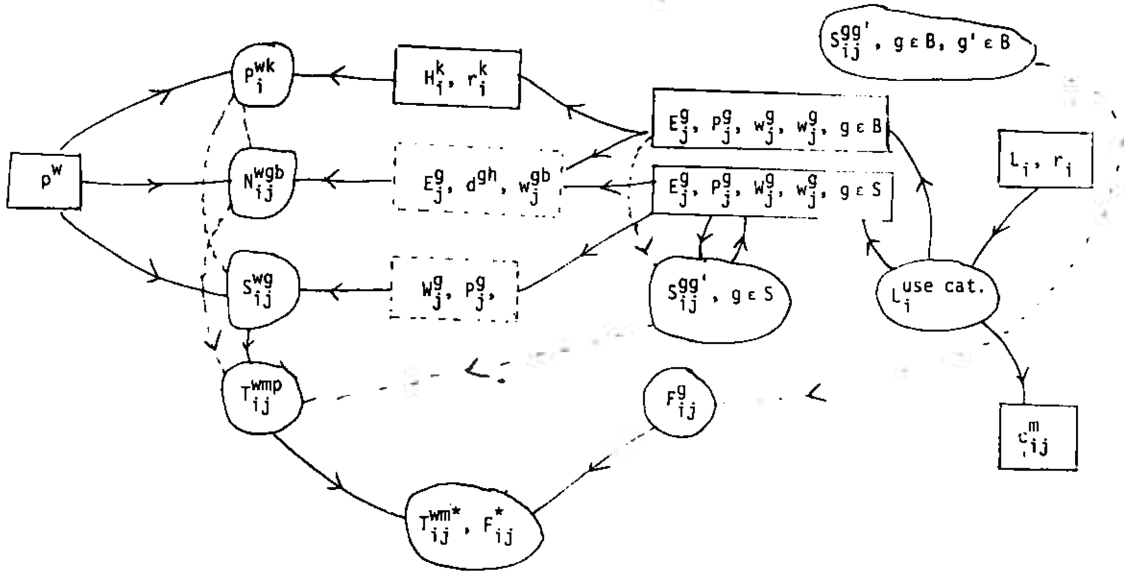
Figure 6. Transport



Key to Figure 7

H_i^k	:	houses by type k at i.
r_i^k	:	rents
L_i	:	land supply
r_i	:	land rent
$L_i^{\text{use cat.}}$	:	land at i by use cat.
P_i^w	:	w-type pop in i.
P_i^{wk}	:	ditto in house type k.
F_{ij}^g	:	flows of goods
N_{ij}^{wgb}	:	w-type p. res in i, wkg in sector g, in occ b in j.
E_j^g	:	emp. in g in j
W_j^g	:	attr. size] of service sector
p_j^g	:	prices of goods
w_j^g	:	wage rates
w_j^{gb}	:	wage rates by occupation group
S_{ij}^{wg}, $S_{ij}^{gg'}$	:	service flows
T_{ij}^{wmp}	:	flows by mode and purpose

Figure 7



p^w
p_i^{wk}
N_{ij}^{wgb}
S_{ij}^{wg}
T_{ij}^{wmp}
H_i^k, r_i^k
E_j^g, d^{gh}, w_j^{gb}
$W_j^g, p_j^g,$
T_{ij}^{wm*}, F_{ij}^*
$E_j^g, p_j^g, w_j^g, w_j^g, g \in B$
$E_j^g, p_j^g, W_j^g, w_j^g, g \in S$
$S_{ij}^{gg'}, g \in S$
F_{ij}^g
$S_{ij}^{gg'}, g \in B, g' \in B$
L_i, r_i
$L_i^{use\ cat.}$
c_{ij}^m

Figure 8. The task of account-based dynamic modelling: connecting two cross-sections

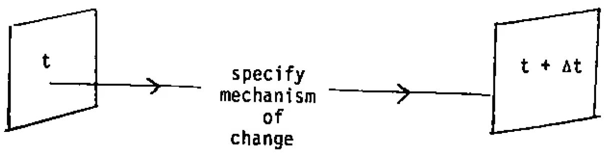
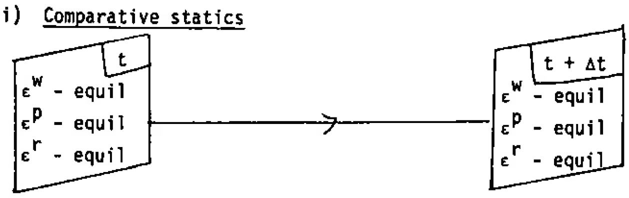
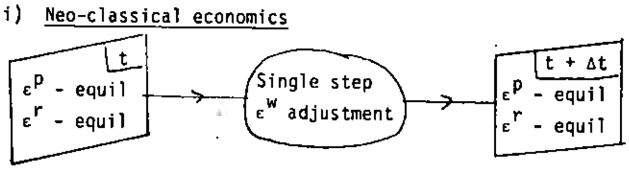


Figure 9. Alternative dynamical model structures

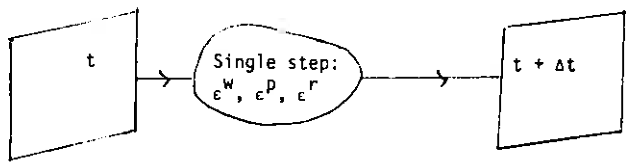
(i) Comparative statics



(ii) Neo-classical economics



(iii) Incremental



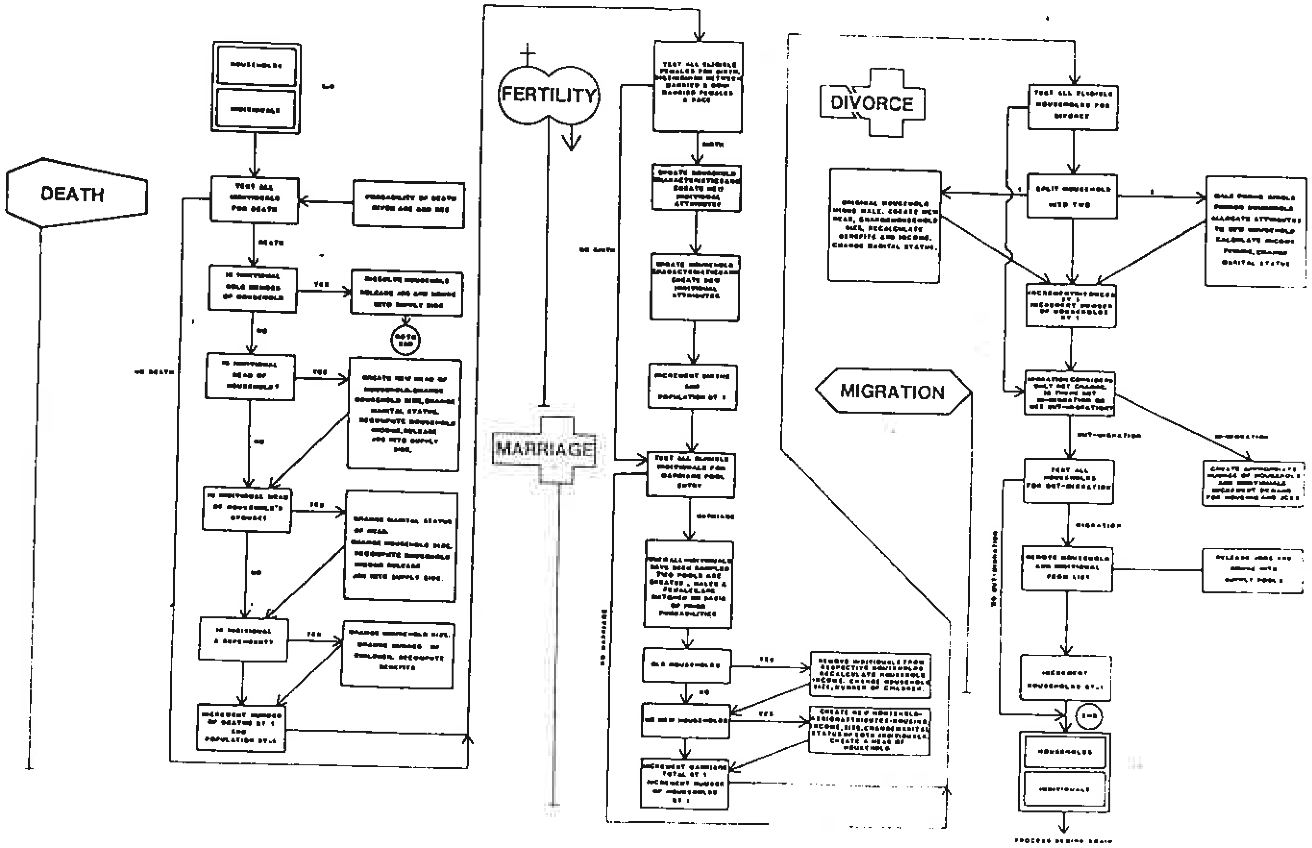
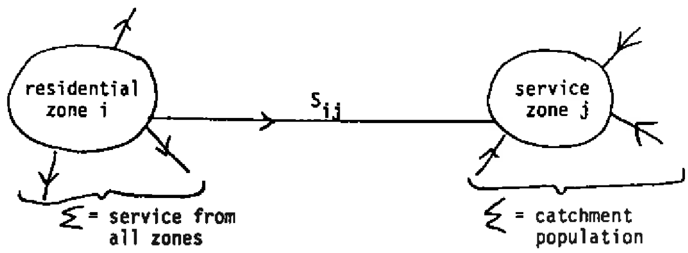


Figure 10. Structure of the Demographic Model and Interdependencies.

Figure 11. Conceptual basis for performance indicators



Typical indicators:

$$\frac{\text{Expenditure in any zone}}{\text{Residential population}} \qquad \frac{\text{Expenditure in service zone}}{\text{Catchment population}}$$

(effectiveness) (efficiency)

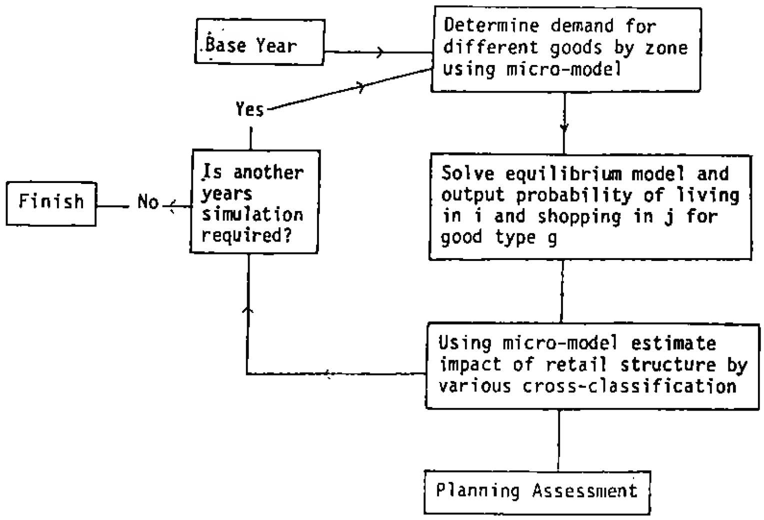


Figure 12. Structure of Integrated Model