New Spatial Planning Models

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Abstract. Recent advances in computer memory and speed and new specialised software for the capture, manipulation and presentation of spatial information have vastly increased the possibilities of spatial planning models. The aggregation error of zones can now be overcome by new and efficient ways of spatial interpolation, spurious equilibrium assumptions can be replaced by the dynamics of different speeds and response patterns, and probabilistic generalisation can give way to one-to-one representations of individual behaviour. These new techniques give rise to new types of spatial planning models, make better use of existing data or even depart for totally new horizons that could not have been approached before.

Introduction

Monitoring and evaluating urban change is an essential ingredient of urban planning and management in both industrialised and developing countries. In industrialised countries the major driving forces of spatial urban development have become private development interests, whereas the authority of local governments to guide and control the direction of urban expansion is being eroded by globalisation, deregulation and a tax system forcing municipalities into competition against each other for tax-paying residents and businesses – the opposite of rational co-operation towards sustainable development. In developing countries, rapid urban growth through rural-to-urban migration leads to unplanned settlements at the fringes of metropolitan areas vastly exceeding the capacity of local governments to enforce safety standards or provide basic infrastructure and services for these settlements, let alone to plan for their socially and economically viable, aesthetically pleasing and ecologically sustainable development.

The causes are different but the result is similar: in both industrialised and developing countries the role of local governments in urban development has changed from that of the primary actor to that of a player among others if not of that of an observer. In this situation cities have to resort to less authoritarian ways of influencing urban development by negotiation, persuasion and incentives rather than by command and control instruments of statutory planning.

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In this situation it is of vital importance for cities to not only know *what* is going on but also *why*, i.e. to *understand* the interests and motives of the relevant private actors – and not only to understand their past and present behaviour but also to predict their likely future plans and actions, in particular their likely response to statutory planning instruments, regulation or incentives.

This is where spatial planning models become important. Spatial planning models achieve more than monitoring in that they proceed beyond *description* to *explanation*. By using theories about human behaviour – habitual or (more or less) rational choice behaviour under constraints (informational, monetary, temporal) – a relevant part of reality, say a city, is re-constructed as a *virtual reality* (in a more general sense) which is, in all relevant features, structurally similar to reality, i.e. responds in a similar way to external stimuli. If that can be demonstrated – the validation step – the model can be used for *forecasting*, i.e. can be exposed to stimuli reflecting expectations about how the world at large will develop, and will predict how the city is likely to respond to these stimuli.

Spatial planning models include regional economic development models, land and housing market models, plant and facility location models, spatial diffusion models, migration models, travel and goods transport models and urban land-use models. More recently environmental impact models have become important, such as weather forecasting models, climate models, air dispersion models, chemical reaction models, rainfall-runoff models, groundwater models, soil erosion models, biological ecosystems models, energy system models and noise propagation models.

Some of these applications have a long tradition. Spatial models in the social sciences date back to von Thünen (1826) and Ravenstein (1885/89). Important pioneering insights into the spatio-temporal nature of complex dynamic systems originated in ecological modelling (Lotka, 1920; Volterra, 1931). However, the real rise of spatial modelling occurred in the 1960s with the general availability of computers. Today global climate models or models simulating flows in large transport networks would not be possible without the memory and speed of computers.

The representation of space in the first generations of spatial computer models was primitive. It essentially followed the organisation of statistical tables where each line is associated with one spatial unit such as a statistical district, region or 'zone' and the columns represent attributes of the areal unit. This was the 'container' view of space in which space was reduced to a receptacle or carrier of spatial phenomena; spatial distributions and spatial interactions within zones were lost. The analogue counterpart of the container view of space was the 'thematic' or choropleth map. Networks were coded as lattices, but because nodes were not associated with coordinates, the geometry of networks was only vaguely represented by the lengths (travel times) of their arcs. Zones were connected to networks by pseudo links ignoring cross-boundary interactions between adjacent zones. This problem could be alleviated but not overcome by increasing the number of zones, as data were expensive to collect and memory was scarce and computers were slow.

All this has changed recently. Computers have grown breathtakingly in memory and computing speed. What would have been called a very large and very fast 'mainframe' computer only a few years ago is now available on the desktop of any researcher. Data that previously had to be manually compiled such as land coverage, transport networks or small-area population and employment data are now routinely made available in digital form in many countries.

However, the greatest change seems to be the advent of specialised software for the capture, manipulation and presentation of digital spatial information, geographic information systems (GIS). These systems, and the surge of theoretical work associated with them, have vastly increased the range of possibilities of organising spatial data beyond the 'container' model of space. The aggregation error of zones can now be overcome by new and efficient ways of spatial interpolation, making use of reasonable assumptions about spatial distributions of attribute data between observation points. Together with the improvements in data availability and the increases in computer memory and speed, these new techniques open up a new world for spatial models. It would be surprising if the new possibilities would not give rise to new types of spatial models which exploit the technological potential now available, make better use of existing data, stimulate the collection of new data or even depart for totally new horizons that could not have been approached before.

This paper will give examples of this new potential. After theoretical remarks on spatial models and their relationship to geographical information systems, two areas will be presented in which deficiencies of current urban planning models can be overcome by the new technical possibilities. Both areas are part of a general tendency of disaggregation of models from macro to micro in substance, space and time. The paper will close with a perspective on ongoing and further work.

Spatial Models

A model is a simplified representation of an object of investigation for purposes of description, explanation, forecasting or planning. A spatial model is a model of an object of investigation in bi-space (space, attribute). A space-time model is a model of an object of investigation in tri-space (space, time, attribute).

There are three categories of spatial models with respect to their degree of formalisation: scale, conceptual and mathematical models (Steyaert, 1993). Scale models are representations of real-world physical features such as digital terrain models (DTM) or network models. Conceptual models use quasi-natural language or flow charts to outline the components of the system under investigation and highlight the linkages between them. Mathematical models operationalise conceptual models by representing their components and interactions with mathematical constructs. In the following discussion the emphasis is on mathematical models.

Another important classification of spatial models is how they deal with the indeterminism of real-world phenomena (Berry, 1995). Deterministic models generate repeatable solutions based on the direct evaluation of defined relationships, i.e. do not contain random variables. Probabilistic models are based on probability distributions of statistically independent events and generate a range of possible solutions.

A third basic classification refers to statics/dynamics. In a static model all stocks have the same time label, i.e. only one point in time is considered. Static models are usually associated with the notion of a steady state or equilibrium. In a dynamic model stocks have two (comparative statics) or more time labels, hence change processes are modelled. Dynamic models may treat time as continuous or discrete. Models with discrete time intervals are called simulation models; with fixed time intervals (periods) they are called recursive, with variable time intervals event-driven.

Spatial models can also be classified according to their resolution and extent in space, time and attributes, ranging from the macroscopic to the microscopic. The space dimension can be represented by objects with zero dimension (points), one dimension (lines), two dimensions (areas) or three dimensions (volumes); spatial resolution may range from a few centimetres to, say, ten kilometres, and the extent of objects may range from a few metres to thousands of kilometres. In similar terms the time dimension can be represented with zero dimension (event) or one dimension (process); the resolution may range between a few seconds and hundreds of years, and the extent of time considered between, say, a day and millions of years (in geologic processes). The attribute dimension may be single- or multiattribute. The resolution of attributes may range from averages of attributes of large collectives (gases, species, national economies) to individual attributes of individual objects (molecules, neurons, travellers), with all stages in between. The extent of attributes may range from an infinite number of possible states to only one possible state. Simulation models of individual objects are called microsimulation models; microsimulation models do not need to simulate all objects of the system of investigation but may work with a sufficiently large sample.

There are many more ways of classifying spatial models that can only be indicated here. Beyond the above criteria, spatial models can be classified by

- comprehensiveness: some models deal only with one spatial subsystem, whereas others deal with interactions between different spatial subsystems.
- model structure: one group of models applies one single unifying principle for modelling and linking all subsystems; other models consist of loosely coupled submodels each of which has its own independent internal structure.
- theoretical foundations: environmental models rely on physical laws, whereas socio-economic models apply theoretical approaches such as random utility or economic equilibrium theory.
- modelling techniques: here techniques such as input-output models, spatial interaction models, neural network models, Markov models or microsimulation might be listed.

Spatial Planning Models

Spatial planning models originated from several disciplines such as economics, geography, sociology and transport engineering and have only since the 1960s been integrated by 'synthetic' disciplines such as regional science or planning. In the urban planning field the following disciplines have contributed:

- *Economic* modelling with a spatial dimension at the metropolitan scale includes models of urban land and housing markets based on the concept of bid rent. Normative economic models based on location theory (minimising location and transport cost) are used to determine optimum locations for manufacturing plants, wholesale and retail outlets or public facilities.
- *Geographical* modelling includes migration models based on notions of distance and dissimilarity between origin and destination location frequently coupled with probabilistic models of population dynamics, spatial interaction and location models based on entropy or random utility concepts and models of activity-based mobility behaviour of individuals subject to constraints ('space-time geography').
- *Sociological* modelling has contributed spatial models of segregation of socio-economic or ethnic groups in urban areas and of invasion of urban territories by popu-

lation groups based on analogies from plant and animal ecology ('social ecology') and models of urban 'action spaces' related to concepts of space-time geography.

- *Transport engineering* modelling includes travel and goods transport models based on entropy or random-utility theory with submodels of flow generation, destination choice, modal choice, network search and flow assignment with capacity restraint resulting in user-optimum network equilibrium, and normative models for route planning, transport fleet management and navigation in large transport networks. In more recent developments, concepts of activity-based mobility have been taken up by transport modellers to take account of non-vehicle trips, trip chains, multimodal trips, car sharing and new forms of demand-responsive collective transport.
- *Integrated* modelling includes approaches in which two or more of the above specialised models are combined, such as integrated models of spatial development at the metropolitan scale. Typically such models consist of models of activity location, land use and travel; more recently also environmental aspects such as energy consumption, CO_2 emissions, air pollution, open space and traffic noise are addressed.

The need for integrative solutions is becoming more urgent because of the interconnectedness of economic, social and environmental problems.

Spatial Models and GIS

There is a growing literature on GIS and spatial models (Fischer and Nijkamp, 1992; Goodchild et al., 1993b; Longley and Batty, 1996; Fotheringham and Rogerson, 1994; Fischer et al., 1996; Fotheringham and Wegener, 2000). However, because of the limited analytical or modelling capabilities of present GIS, the tools offered by current GIS appear to be of little interest for spatial modelling. Instead it seems to be more relevant to examine whether the organisation of spatial information in GIS is appropriate for spatial models and how spatial models might be linked with GIS.

The typical forms of data organisation of urban planning models are very similar to those of present GIS (see Table 1). However, there is no equivalent to interaction matrices in present GIS. The main advantages of data organisation in GIS are the ease of data capture or data entry, data manipulation and visualisation. Another important advantage is the possibility to co-process data stored in different data models. In conjunction with appropriate spatial interpolation techniques, it is possible to co-process polygon-based, network-based and list-based spatial models in one common spatial framework. For instance, in a travel simulation one might use a list to sample trip origins from a population surface created by spatial interpolation from zonal data, access the nearest network node pixel, perform destination, mode and route choice on the link-coded network and return to pixel representation at the destination. The results may be used as link-by-link information to drive a capacity-restraint or network-equilibrium model or may be used as pixel-by-pixel input to environmental impact submodels or to drive output routines generating 2D or 3D surface representations.

Nyerges (1992) proposed a conceptual framework for the coupling of spatial models with GIS. He distinguishes between four ways of linkage with increasing intensity of coupling: isolated applications, loose coupling, tight coupling and full integration. An external model offers the advantage of independent and flexible development and testing of the model, but is suitable only for loose coupling. Embedding the spatial model into the GIS has the advantage that all functions and data resources of the GIS can be used. Until recently this has been difficult to achieve but is now a standard capability of the component-based software architecture of some GIS products. Specific modelling languages, such as STELLA (High Performance Systems, Inc., Hanover, NH) or SWARM (Swarm Development Group, Santa Fe, NM) or PCRaster (PCRaster Environmental Software, Utrecht, NL) offer tools for combining spatial models with GIS functions; however the range of models that can be defined is limited.

Table 1. Data organisation of models and GIS

Data objects	Model data organisation	GIS data organisation
Area data	Stock matrix: a two-dimensional matrix where the rows indicate the areas and the columns contain attributes. It is implicitly assumed that attributes are uniformly distributed throughout the area.	Polygons: areas are represented as polygons and area data are stored in polygon attribute tables. It is implicitly assumed that attributes are uniformly distributed throughout the polygon.
Interaction data	Interaction matrix: square matrix where rows and columns represent areas. The cells of the matrix contain impedances or flows between areas.	There is no equivalent to interaction matrices in GIS.
Network data	Link: each link record is identified by from-node and to-node and contains link attributes such as length, travel time, capacity. The alignment is not coded.	Links are stored as arcs and link attributes in arc attribute tables. The alignment is also coded. The convenience of digitising and editing links is an advantage.
Point data	List: a sequence of records where each record refers to an object (a household, a firm, a building) in an area. Each record contains attributes of the object; the location in the area is not recorded.	Point data are stored in point attribute tables. The advantage is that points have micro locations, i.e. pairs of co-ordinates.
Area/point data	Raster: the topology is implicit in the data model, which simplifies processing. If the raster cells are small, quasi-continuous surfaces can be constructed.	Raster-based GIS correspond directly to raster-based models with raster attributes stored in value attribute tables.

First Experience

There is today a wide spectrum of urban planning models using GIS (see Spiekermann and Wegener, 2000). However, in only few of them GIS play a role beyond data base or mapping functions.

In general spatial models in the social sciences use loose coupling. One example is the California Urban Futures Model (Landis 1994) developed at the University of California at Berkeley as a disaggregate model of land use housing development, one of the first urban models to utilise GIS technology (see Landis and Zhang, 1998a; 1998b; 2000). A typical model run requires multiple data transformations between different data formats. Batty and Xie (1994a; 1994b; 1994c) are using strong coupling to link a GIS (ArcInfo) with a large number of external analysis and modelling routines under a common graphical user interface. They note, however, that in their application the GIS is essentially a storage and display medium, and if processes are to be modelled in whatever geographical domain, such modelling must be achieved outside the GIS.

A more radical approach is to start from the modelling side and add GIS functionality by emulating the needed analysis and display functions by subroutines within the model. As only a very small subset of GIS functions are normally required in any one modelling context, the development effort may be justified if the number of applications is sufficiently large. The benefits of this strategy are substantial as one gets rid of all the overhead and limitations of a particular GIS software package. This strategy has been followed, for instance, by Birkin et al. (1990).

An ambitious attempt to overcome the lack of dynamics of GIS and at the same time to exploit the potential of GIS to switch between different representations of space is the Time Geographic Simulation System developed at the Université Paris 1 (Mathian et al., 2000). The TGSS is of hybrid raster type and all geographical objects are defined as aggregations of pixels. The system can handle several hierarchies of scales and, with procedures of aggregation and disaggregation, is able to associate data corresponding to different geographical scales in the same model. To establish the time dimension, all data are stored as temporal series of maps.

New Challenges

What these pioneer applications have in common, is their tendency towards more disaggregate models, and indeed the move from macro to micro seems to be one of the most important advantages of the new technological potential. The trend to disaggregation coincides with new issues coming up in planning which cannot be studied with the previous aggregate models. For instance, new intermodal travel alternatives such as park-and-ride and 'kiss-and-ride', new forms of paratransit such as car-sharing, shared taxis or buses on demand and new life styles and work patterns such as part-time work, telework and teleshopping cannot be modelled by traditional aggregate four-step travel models. New activity-based travel models addressing these issues require more detailed information on household demographics and employment characteristics. New neighbourhood-scale planning policies to promote the use of public transport, walking and cycling require more detailed information on the precise location of activities. New concepts of intermodal urban goods transport ('city logistics') require detailed knowledge on the location of local shippers and recipients. In addition the models need to be able to predict not only economic but also environmental impacts of land-use transport policies, and this requires small area forecasts of emissions from stationary and mobile sources as well as of air quality in terms of exposed population.

Existing urban models are too aggregate to respond to these challenges. Typical models distinguish only few industries, socio-economic groups and dwelling categories, too few to take account of new production and distribution technologies and emerging life styles and work patterns. Moreover, most urban models get their spatial dimension through a zonal system in which it is assumed that all attributes are uniformly distributed throughout a zone. Spatial interaction between zones is established via networks linked only to the centroids of the zones. Zone-based spatial models do not take account of topological relationships and ignore that socio-economic activities and their environmental impacts are continuous in space.

The limitations of zonal systems have led to serious methodological difficulties such as the 'modifiable areal unit problem' (Openshaw, 1984; Fotheringham and Wong, 1991) and problems of spatial interpolation between incompatible zone systems (Flowerdew and Openshaw, 1987; Goodchild et al., 1993a; Fisher and Langford, 1995).

The captivity of spatial modelling in the straitjacket of zonal systems has seriously restricted their capability to respond to current planning issues. For instance, zone-based models lack the spatial resolution necessary to represent environmental phenomena other than energy consumption or CO_2 emissions. Flow models such as air dispersion, noise propagation and surface and ground water flow models require a much higher spatial resolution. Air distribution models work with raster data of emission sources and topographic features such as elevation and surface characteristics such as green space, built-up area and high-rise buildings. Noise propagation models require spatially disaggregate data on emission sources, topography and sound barriers such as dams, walls or buildings as well as the three-dimensional location of population. Surface and ground water flow models require spatially disaggregate data on river systems and geological information on ground water conditions. This implies that not only the *attributes* of the components of the modelled system are of interest but also their physical *micro location.*

These considerations suggest a fundamentally new organisation of urban models based on a microscopic view of urban development (Wegener and Spiekermann, 1996a).

Disaggregation of Spatial Data

The main argument against such a view could be that micro data of households and workplaces, residences and businesses are rarely available, and where they are, their use would be heavily restricted for privacy reasons. In particular in developing countries with poorly developed data infrastructure, micro data may be unavailable.

However, even where no micro data are available, GIS can be used to generate a synthetic disaggregate spatial microdatabase which corresponds to all known statistical distributions (Bracken and Martin, 1989, 1995; Martin and Bracken, 1991; Wegener and Spiekermann, 1996b) and can be used instead of real micro data.

To spatially disaggregate spatially aggregate data within a spatial unit such as an urban district or a census tract, the land use distribution within that zone is taken into account, i.e. it is assumed that there are areas of different density within the zone. The spatial disaggregation of zonal data therefore consists of two steps, the generation of a raster representation of land use and the allocation of the data to raster cells. Fig. 1 illustrates the two steps for a simple example. The following steps are performed:

- First, the land use coverage and the coverage containing the zone borders are overlaid to get land use polygons for each zone. Then the polygons are converted to a raster representation by using a point-in-polygon algorithm for the centroids of the raster cells. As a result each cell has two attributes, the land use category and the zone number of its centroid. These cells represent the addresses for the disaggregation of zonal data and the subsequent microsimulation. The cell size to be selected depends on the required spatial resolution of the microsimulation and is limited by the memory and speed of the available computer.

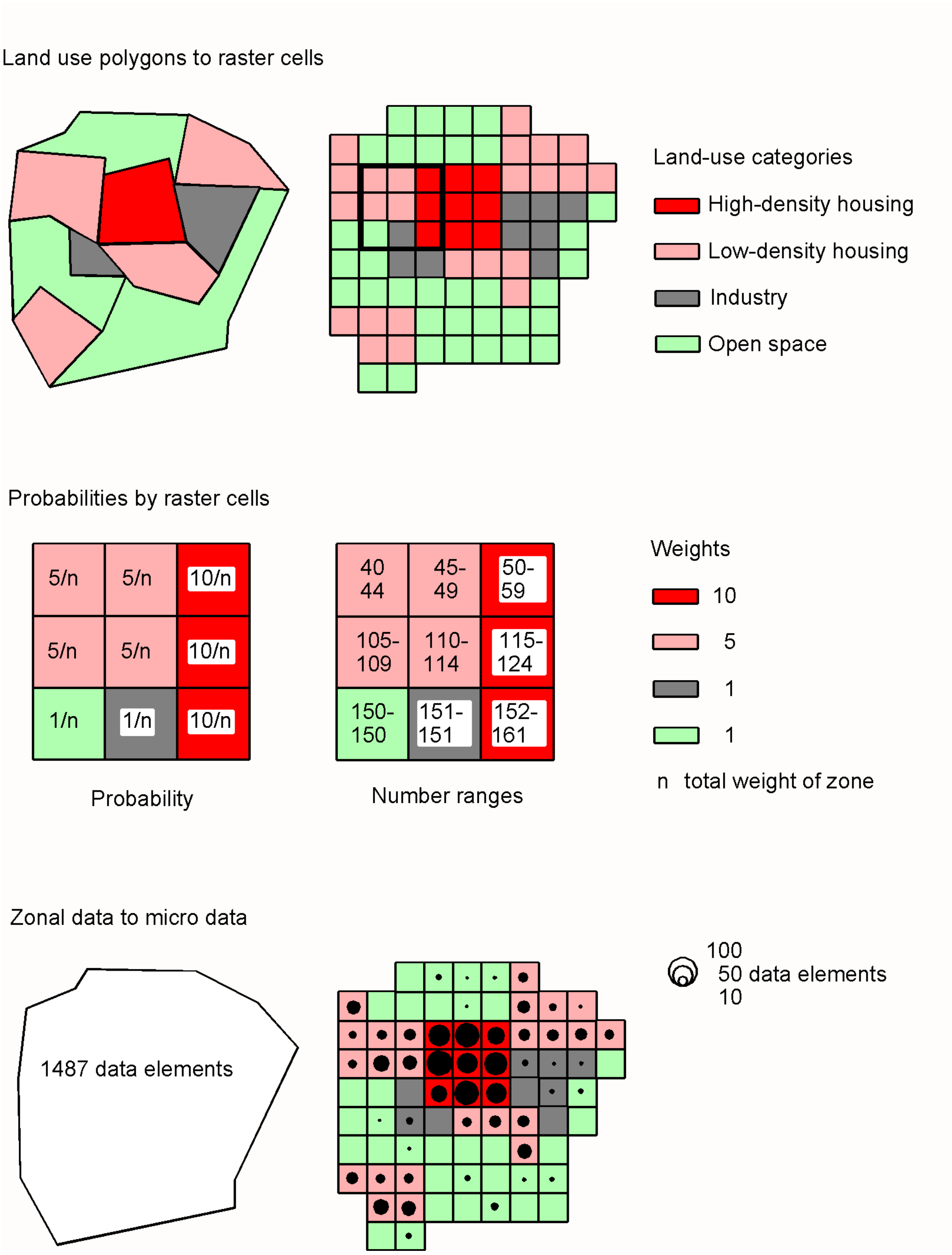

Fig. 1. Spatial disaggregation of zonal data to raster cells

- The next step merges the land use data and zonal activity data such as population or employment. First for each activity to be disaggregated specific weights are assigned to each land use category. Then all cells are attributed with the weights of their land use category. Dividing the weight of a cell by the total of the weights of all cells of the zone gives the probability that this cell will be the address of one element of the zonal activity. Cumulating the weights over the cells of a zone one gets a range of numbers associated with each cell. Using a random number generator for each element of the zonal activity one cell is selected as its address. The result of this is a raster representation of the distribution of the activity within the zone.

Figs. 2 and 3 demonstrate how this method was used for disaggregate environmental impact analyses in the Helsinki application of the SPARTACUS project (LT Consultants et al., 1998).

In the application, an integrated land-use transport model (MEPLAN) was applied to the metropolitan area of Helsinki on the basis of land-use and travel analysis zones. In order to analyse air quality and exposure to traffic noise at a higher spatial resolution, population and land use in the metropolitan region was disaggregated to 100x100 m raster cells using the method described above. The links of the transport network, which were used in vector form in the transport model, were also disaggregated to raster cells as linear emission sources.

Fig. 2 shows the distribution of population and employment in the metropolitan region in three-dimensional form. The 3D plots illustrate the more dispersed distribution of residences across the metropolitan area and the strongly peaked concentration of workplaces in the city centre.

Fig. 3 shows two results of the disaggregate environmental impact analysis. The map of exposure to NO_2 (top) shows the effect of the prevailing wind direction resulting in bands of increased exposure along the north-eastern side of major traffic arteries, whereas the map of exposure to traffic noise (bottom) replicates these as wide corridors. As also the residential population of each raster cell is known, it is possible to calculate the percent of persons exposed to pollution or noise beyond a certain level, an information of high relevance for spatial equity.

The combination of the raster representation of activities and the vector representation of the transport network provides a powerful data organisation of land use, transport and environment in urban regions:

- The raster representation of activities allows the calculation of micro-scale equity and sustainability indicators such as accessibility, air pollution, water quality, noise, micro climate and natural habitats, both for exogenous evaluation and for endogenous feedback into the residential construction and housing market submodels.
- The vector representation of the network allows to apply efficient network algorithms known from aggregate transport models such as minimum path search, mode and route choice and equilibrium assignment. The link between the micro locations of activities in space and the transport network is established by automatic search routines finding the nearest access point to the network or nearest public transport stop.
- The combination of raster and vector representations in one model allows to apply the activity-based modelling philosophy to modelling both location and mobility in an integrated and consistent way. This vastly expands the range of policies that can be examined. For instance, it is possible to study the impacts of public-transport oriented land-use policies promoting low-rise, high-density mixed-use areas with short distances and a large proportions of cycling and walking trips as well as new forms of collec-

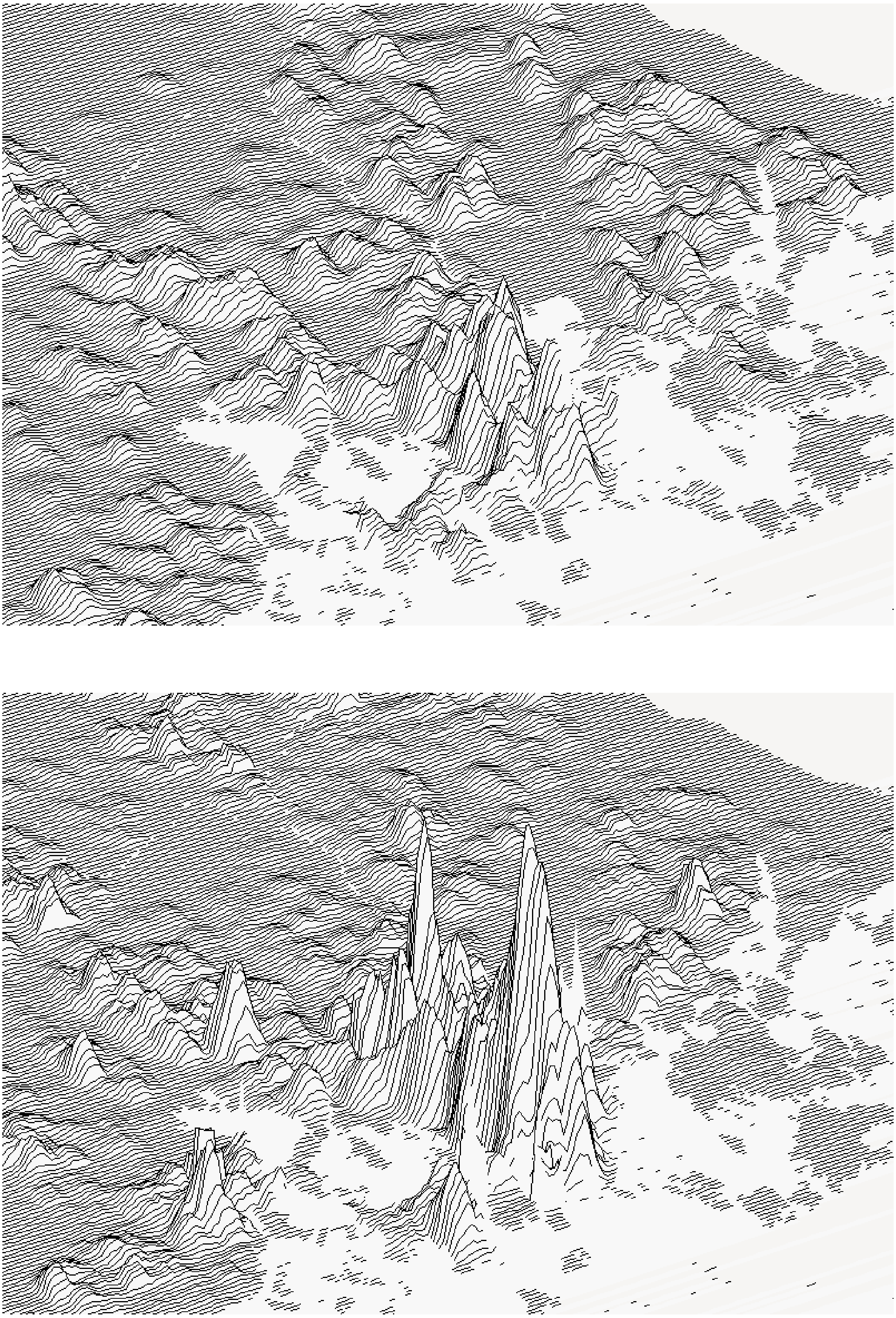

Fig. 2. Population (top) and employment (bottom) in Helsinki (Spiekermann, 1999)

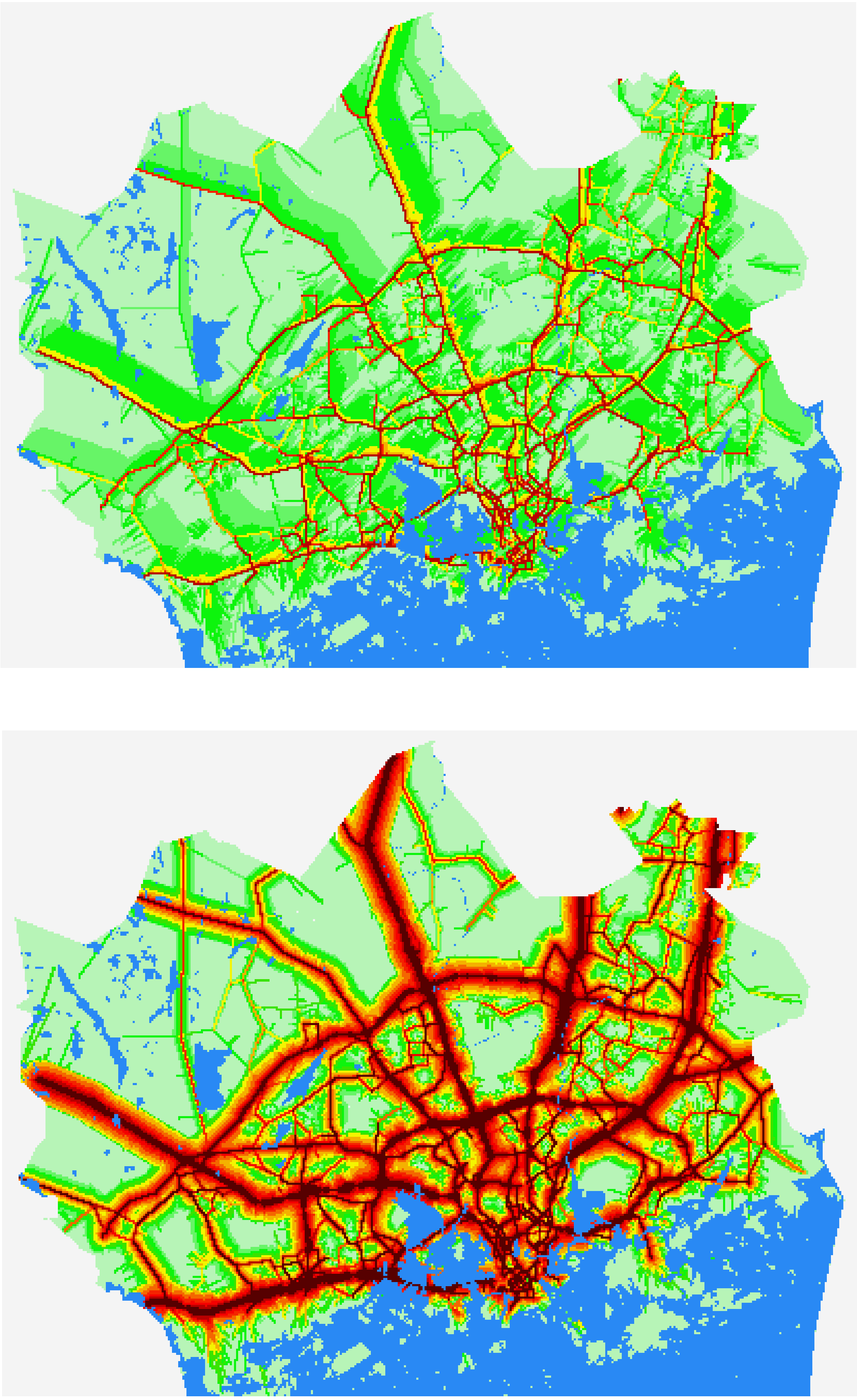

Fig. 3. Exposure to NO_2 (top) and traffic noise (bottom) in Helsinki (Spiekermann, 1999)

Microsimulation

Microsimulation was first used in social science applications by Orcutt et al (1961), yet applications in a spatial context remained occasional experiments without deeper impact, though covering a wide range of phenomena such as spatial diffusion (Hägerstrand, 1968), urban development (Chapin and Weiss, 1968), transport behaviour (Kreibich, 1979), demographic and household dynamics (Clarke et al., 1980; Clarke 1981; Clarke and Holm 1987) and housing choice (Kain and Apgar, 1985; Wegener, 1985). Only recently microsimulation has found new interest because of its flexibility to model processes that cannot be modelled in the aggregate (Clarke, 1996). Today there are several microsimulation models of urban land use and transport under development (Hayashi and Tomita 1989; Mackett 1990a; 1990b; Landis, 1994; Landis and Zhang, 1998a; 1998b; 2000; Waddell, 1998a; 1998b; Wegener and Spiekermann, 1996b).

A different approach emerged from the theory of cellular dynamics. Cellular automata (CA) are objects associated with areal units or *cells*. CA follow simple stimulus-response rules to change or not to change their *state* based on the state of adjacent or near-by cells. By adding random noise to the rules, surprisingly complex patterns that closely resemble real cities can be generated (White and Engelen, 1993; Batty and Xie, 1994a; 1994b; 1994c; Batty, 1997). More complex stimulus-response behaviour is given to CA models in multi-reactive agents models. Multi-reactive agents are complex automata with the ability to control their interaction pattern; they can change their environment but also their own behaviour, i.e. are able to learn (Ferrand, 2000). The distinction between the behaviour of multi-reactive agents and the choice behaviour generated in microsimulation models is becoming smaller.

Probably the most advanced area of application of microsimulation in urban models is travel modelling. Aggregate travel models are unable to reproduce the complex spatial behaviour of individuals and to respond to sophisticated travel demand management measures. As a reaction, disaggregate travel models aim at a one-to-one reproduction of spatial behaviour by which individuals choose between mobility options in their pursuit of activities during a day (Axhausen and Gärling, 1992; Ben Akiva et al., 1996; Veldhuisen et al., 2000). Activity-based travel models start from interdependent 'activity programmes' of household members and translate these into home-based 'tours' consisting of one or more trips. This way interdependencies between the mobility behaviour of household members and between the trips of a tour can be modelled as well as intermodal trips that cannot be handled in aggregate multimodal travel models. Activity-based travel models do not model peak-hour or all-day travel but disaggregate travel behaviour by time of day, which permits the modelling of choice of departure time. There are also disaggregate traffic assignment models based on queuing or CA approaches, e.g. in the TRANSIMS project (Nagel et al., 1999; Barrett et al., 1999), which reproduce the movement of vehicles in the road network with a level of detail not known before.

Microsimulation Modules

Whereas in the SPARTACUS project the urban simulation was still aggregate and only the subsequent environmental submodels disaggregate, the model described in this section is disaggregate throughout, i.e. is fully based on microsimulation.

Each microsimulation module is a separate software procedure with defined input and output interfaces, and each models a particular kind of change process. There are three kinds of process (cf. Wegener, 1985):

- *Transitions*. A transition represents a change from one state to another. A typical transition for instance is the evolution of a household during a certain time interval during which it is promoted to another household category with respect to nationality, age, income or size conditional on the relevant probabilities for events such as migration, birth of child, ageing/death, marriage or divorce, or the development of a firm from establishment through growth and decline to closure. Choice-based events such as marriage or divorce may be treated as transitions if the causal chain behind them is of no interest for the purpose of the model.
- *Choices*. A choice represents a selection between alternatives. A typical choice represents for instance the behaviour of a household looking for a dwelling in the housing market. Its propensity to move depends on its satisfaction with its present dwelling. It first chooses a neighbourhood in which to look for a dwelling, and this depends on its present residence and work place. The household then looks for a dwelling in that neighbourhood guided by the attractiveness and price of vacant dwellings there. The household accepts a dwelling if it can significantly improve its housing condition. If it declines, it enters another search phase.
- *Policies*. Choices in which the decision maker is a public authority represent decisions by which the public authority intervenes in the process of urban development.

The list of microsimulation modules ordered by increasing speed of change from slow to fast changes is presented in Table 2.

Table 2. Microsimulation modules

Module	Period	Submodules
Infrastructure	5 years	Roads, public transport
Buildings	3 years	Residential, business
Households	2 years	Household life cycles, person life cycles
Firms	2 years	Business life cycles
Location	1 year	Residential location, business location
Vehicles	1 year	Cars, commercial vehicles
Activities	1 day	household activities, logistics
Transport	1 day	Travel, goods transport

All microsimulation modules access a common spatial data base. Access is controlled by a scheduler programme that takes into account the nested structure of different speed and frequency of occurrence of the change processes modelled. Access to the database is restricted by rules that give each module specific privileges to change particular data items.

The common spatial database consist of lists of households (with associated household members), firms (with associated workers), residential and non-residential buildings (with associated dwellings and business locations) and other facilities. Households, firms, buildings and facilities are located by micro locations. Micro locations are pairs of co-ordinates indicating a row and a column in a matrix of raster cells.

In order to give an idea of the composition of the microsimulation modules, three basic microsimulation modules will be presented below.

Household Formation

The household formation microsimulation module models the evolution of household attributes associating each household with a particular life style.

Life style is an empirical concept that attempts to capture human spatio-temporal behaviour. It can be viewed as the sum of activities, distributed in time, space, inter-personal and intra-personal dimensions. It is a physical expression of the pattern of activities which the individuals aspire to engage in subject to constraints (Salomon, 1983). For the purpose of forecasting behaviour, the concept of life style seems to be richer in information than the conventional classification of market segments along socio-demographic and economic variables. As life style expresses the aspiration one has with regard to the way of living (i.e. activities in time and space), peoples' revealed behaviour is either consistent with their aspirations or a deviation thereof in the presence of constraints. Thus, identifying a person's life style is expected to be instrumental in predicting her behavioural responses to new situations.

In the social sciences life styles usually are represented in the form of free-form narratives or ‘stories’. The story format, though open and potentially rich in content, is not suitable for mathematical modelling. Therefore life styles need to be translated from the open narrative format to some kind of quantitative representation which, however, should preserve as much of the variation in life styles found in reality. Such a representation is the representation of life styles as fuzzy objects. In the proposed model a ‘life style’ therefore is a fuzzy object defined by a set of probabilistic membership functions. A probabilistic membership function is a vector of probabilities specifying the likelihood that individuals with a particular life style belong to a particular category of a set of classified attributes.

The probabilities of the membership functions can be found as observed frequencies in empirical investigations, e.g. household surveys. In the absence of such surveys they are determined by expert judgement and validated against observed aggregate distributions. The validation is performed by microsimulation by which a synthetic spatially disaggregate population of individuals and households is generated that as far as possible conforms to the membership functions defining each life style, aggregate observed distributions such as population by age and sex, and the observed spatial distribution of land use and activities by zone.

Households are stored in list form. A list is here a sequence of fixed-length records, where each record contains information on one household. Households may appear in the list in any order, as search in the list is performed with the help of associated lists of pointers. Records contain attributes of households and pointers to records with attributes of its members in an associated list of persons.

In the household formation module the following household events are modelled simultaneously for households and household members (see Fig. 4):
- birth, ageing, death
- new household, dissolution of household
- marriage/divorce, cohabitation/separation, separation of child, person joins
- new job, retirement, unemployment
- change of income

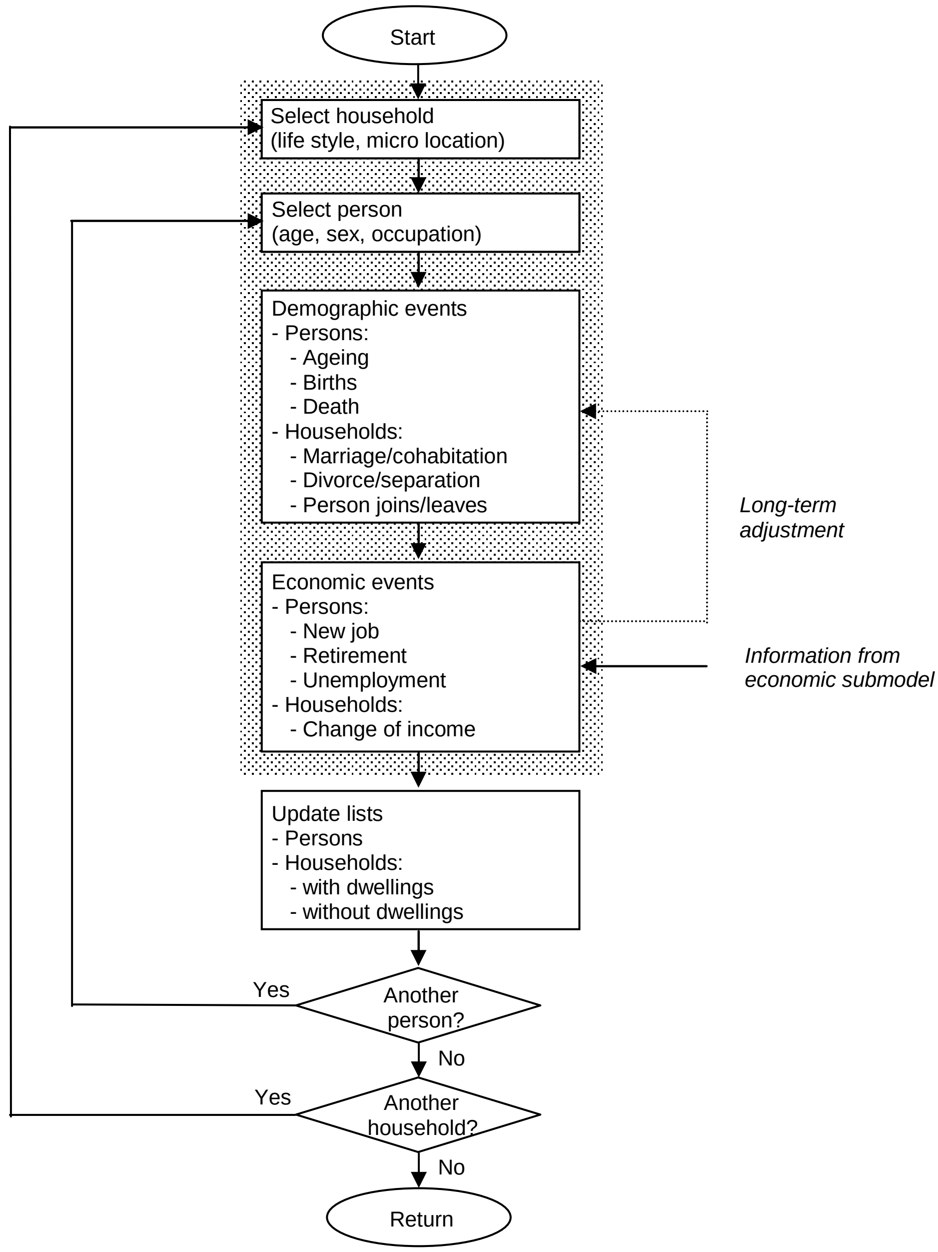

Fig. 4. Microsimulation of household formation: one year

Even though household formation events in reality are the outcome of more or less rational decisions, most of them will not be modelled as decisions but as transitions, i.e. simply as the result of the passage of time. Typical transitions are, for instance, changes of the state of a household with respect to age or size conditional on the relevant probabilities for events such as ageing/death, birth of child, relative joins or leaves household. Also clearly choice-based events such as marriage or divorce are modelled as transitions because the causal chain behind them is not represented in the model. Some events result in the dissolution of households or the creation of new households. Other events, such as a new job or unemployment are triggered by external events such as hiring or firing in the labour market of the model. Change of income is a consequence of employment-related events.

Beyond these straightforward relationships there is wide scope in the model for introducing more complex interdependencies between household and economic events. For instance, the rise of dual worker households may be in part a life style choice and in part a necessity dictated by rising housing costs and stagnant real incomes. Children may delay new household formation or marriage. Childbearing may be postponed based on some combination of life style preferences and response to housing cost and earnings expectations. The role of labour market expectations in shaping these choices is an area of considerable policy implications.

Housing Choice

The housing choice microsimulation module models location and housing choice decisions of households who move into the region (immigration), move out of the region (outmigration), move into a dwelling for the first time (starter households) or have a dwelling and move into another dwelling (moves). Households and dwellings are organised in four associated lists:

- The first list is the list of households (with its associated list of household members) maintained in the household formation submodel.
- The second list contains households without dwelling; households remaining in this list at the end of each simulation period are homeless.
- The third list contains dwellings with their micro locations and attributes.
- The fourth list contains vacant dwellings; it is continuously updated during the microsimulation.

Dwellings are affected by ageing and by decisions on new construction, upgrading and demolition modelled in other submodels not described here.

The housing choice model is a Monte Carlo microsimulation of transactions in the housing market. A market transaction is any successfully completed operation by which a household moves into or out of a dwelling or both. There are two types of actors in the housing market: households looking for a dwelling (housing demand) and landlords looking for tenants or buyers (housing supply). A market transaction has four phases (see Fig. 5):

- In the *sampling* phase a household looking for a dwelling or a landlord looking for a tenant or buyer is selected for being simulated. The probability that a household looking for a dwelling is selected is a function of its dissatisfaction with its present dwelling.

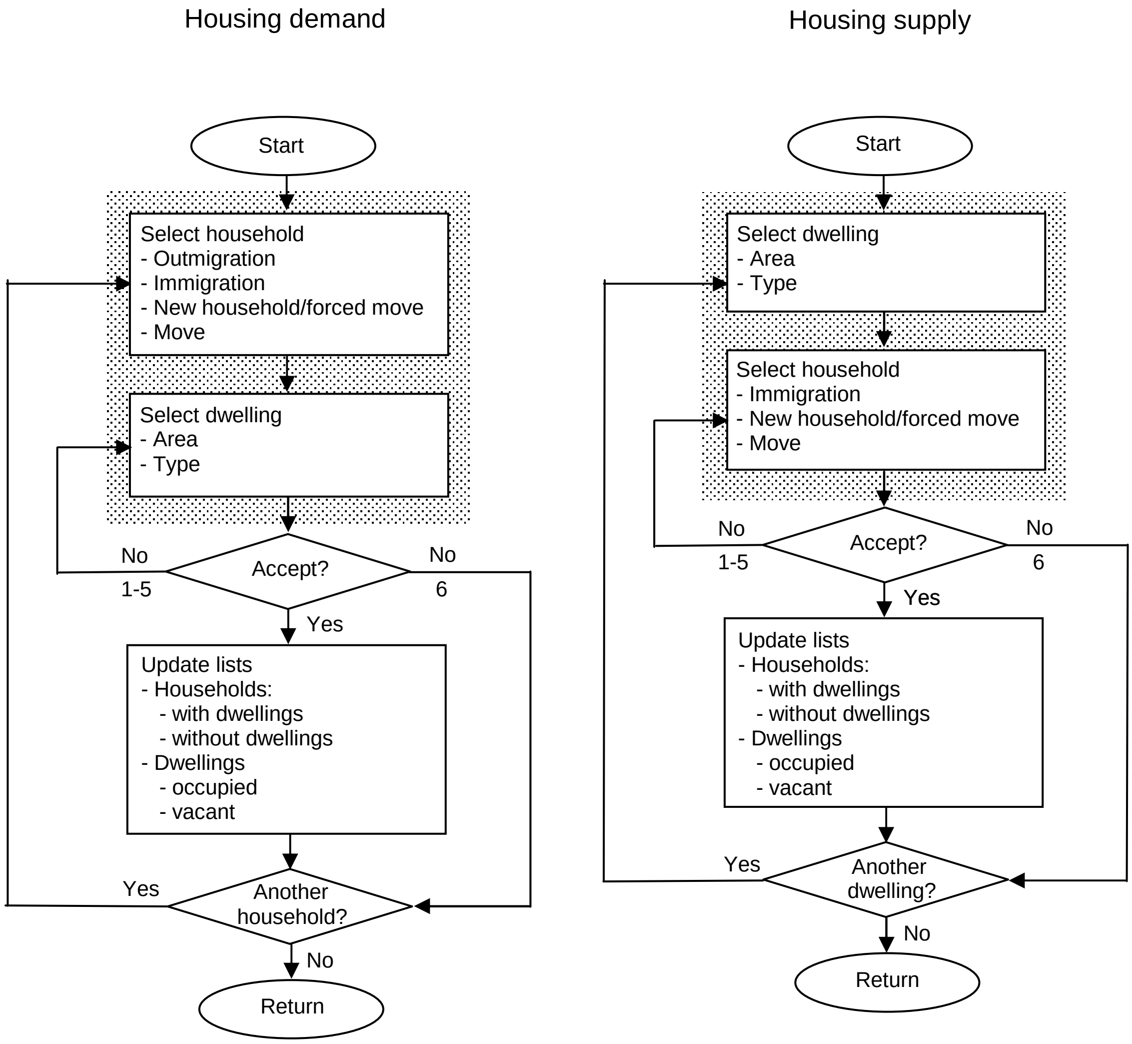

Fig. 5. Microsimulation of housing choice: one year

- In the *search* phase the household looks for a dwelling or the landlord looks for a tenant or buyer. The probability that the selected household searches for a new dwelling in a particular part of the city is a function of the attractiveness of that part of the city as perceived by the household. The probability that the household inspects a certain dwelling in that area is a multiattribute logit choice function of its attractiveness as perceived by the household.
- In the *choice* phase the household decides whether to accept the dwelling or not. It behaves as a satisficer, i.e. it accepts the dwelling if this will improve its housing situation by a considerable margin. Otherwise, it enters another search phase, but after a number of unsuccessful attempts it abandons the idea of a move. The amount of improvement necessary to make a household move is assumed to depend on its prior search experience, i.e. go up with each successful and down with each unsuccessful search. In other words, households adapt their aspiration levels to supply conditions on the market.

- In the *implementation* phase all changes of households and dwellings resulting from the transaction are performed. Dwellings that are occupied are removed from the vacant dwellings list. Dwellings that are vacated are added to it. Households that moved into a dwelling are removed from the list of households without dwelling and are associated with a dwelling. Households that moved from one dwelling to another are dissociated with the old dwelling and associated with the new dwelling.

The attractiveness of a dwelling for a household is a weighted aggregate of the attractiveness of its location, its quality and its rent or price in relation to the household's housing budget. The attractiveness of the location and the quality of the dwelling are themselves multiattribute encompassing relevant attributes of the neighbourhood and of the dwelling.

Travel Behaviour

The travel behaviour module simulates for each member of each household the selection of an activity programme and, subject to that selection, for each tour a tour departure time and for each trip a trip departure time, destination, mode and route (see Fig. 6):

- *Select household*. In the first step a household is selected from the list of households. The selection has to be spatially random to ensure a non-biased assignment to the network (see below). Each selected household is defined by its household attributes and its associated life style and by the personal attributes of its members. The household attributes include its residential location. A location in the model is a micro location, i.e. street address, geographical co-ordinates, or a raster cell (see below).
- *Select person*. Next the first household member is selected. For each working person in the household the location of the workplace is known. For school children and university students the location of the school or university is known.
- *Select activity programme*. Depending on the attributes of the household member, i.e. age, sex and occupation and workplace, a daily activity pattern is selected from a catalogue of activity patterns. A daily activity pattern is defined as a schedule of tours.
- *Select car ownership and availability*. Depending on household and personal attributes it is determined whether the person has a car at his or her disposal.
- *Selection of trip departure time*. The first trip of the tour is selected. The departure time is determined as a random variation of the scheduled departure time.
- *Select destination*. The destination of the trip is selected by logit choice. The locations of destinations are micro locations as above. Generalised costs of travel to the destinations are calculated as the logsum of stochastic minimum paths (see below) of relevant modes. Relevant modes are walk, bicycle, public transport and car (if available, see above). For work, school and university trips the destinations are already known.
- *Select mode*. For the selected destination, mode choice is performed by logit choice based on the generalised costs of stochastic minimum paths (see below).
- *Select route*. For the selected mode the stochastic minimum path is selected as route. The stochastic minimum path is the minimum path with a random disturbance added to each link impedance and each waiting/transfer time in the public transport network.
- *Move person through network*. Each person travelling through the network is recorded on each traversed link by 10-minute time interval.
- *Update link travel times*. After each trip, the travel times of all traversed road links are updated to account for congestion.

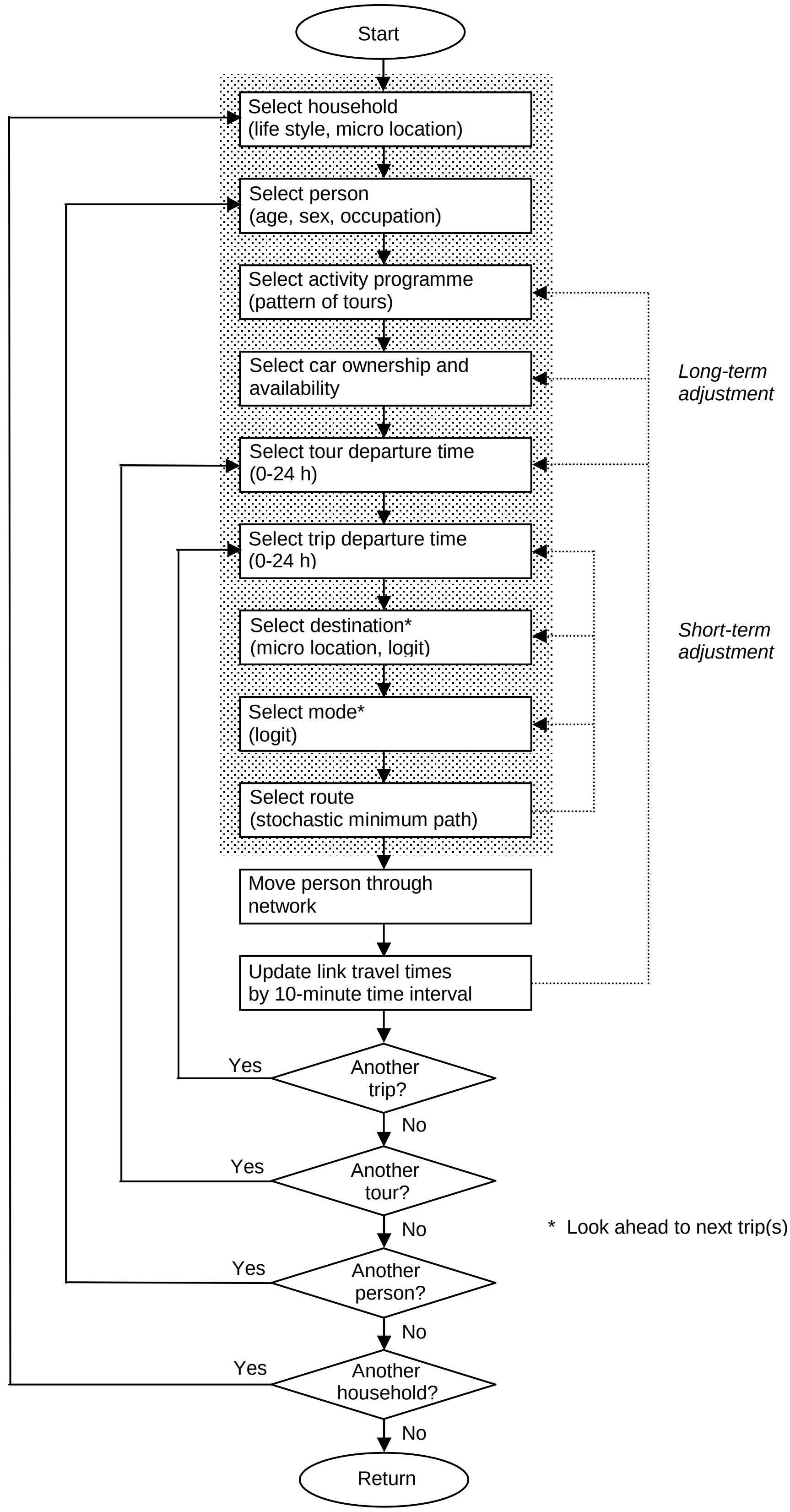

Fig. 6. Microsimulation of travel behaviour: one day

If during a trip significant congestion is encountered, short-term adjustment resulting in postponement of the trip or a change of mode or route may occur. After each trip the next trip of the route, if any, is selected. After each route, the next route, if any, is selected. After each person, the next person, if any, is selected. After each household, the next household, if any, is selected. In order to facilitate long-term learning, information on the generalised costs of the congested network by time of day of the current simulation period is used in the next period.

One important objective of this approach to traffic microsimulation will be to accomplish realistic assignment of travellers to modes and routes without extensive iteration, as computing requirements of iterative assignment in large urban road networks has proved to be a serious problem in TRANSIMS (Nagel et al., 1999).

Ongoing and Future Work

The land-use modules of the microsimulation model outlined above are being implemented in a three-year multi-university research project funded by the Federal Ministry of Education and Research. The project 'Integrated Land-Use Modelling and Transportation System Simulation' (ILUMASS) aims at the development of a microscopic dynamic transport and land use planning support system for the simulation of complex scenarios of spatial urban development. The case study region will be the metropolitan region of Dortmund.

In addition it is planned to implement all microsimulation models, including logistics, goods transport, household activities and travel, by incorporating them into the existing aggregate land-use transport model developed at IRPUD (Wegener, 1998). The IRPUD model is well suited for the integration of microsimulation modules. The microsimulation of household formation and travel behaviour correspond to existing aggregate submodels. These will be replaced by the microsimulation modules. The microsimulation of housing choice will replace the present hybrid microsimulation which is disaggregate in its modelling of behaviour but spatially aggregate in its data.

Certain complications will arise with respect to the spatio-temporal database underlying the model. In the present model all simulation results of each simulation period are written into the spatio-temporal database on a zonal basis for use in the next simulation period. After the simulation all results are contained in the database for ex-post analysis and the production of diagrams and maps. This implies that the microsimulation modules of household formation and housing choice will have to maintain their own disaggregate database consisting of the lists of households, household members and dwellings described above. It is planned that for compatibility reasons the microsimulation data will also be stored in aggregate form in the present aggregate database.

The micro locations used in the microsimulation modules will be implemented in the IRPUD model by raster cells, where a micro location is a pair of co-ordinates indicating the row and column in a matrix of raster cells. The size of the raster cells will be 100x100 m. As no micro household and workplace data are available for the Dortmund metropolitan area, aggregate data for statistical districts and sub-districts will be disaggregated using the method described above.

Fig. 7 presents the integrated microsimulation urban simulation model and the subsequent environmental impact submodels.

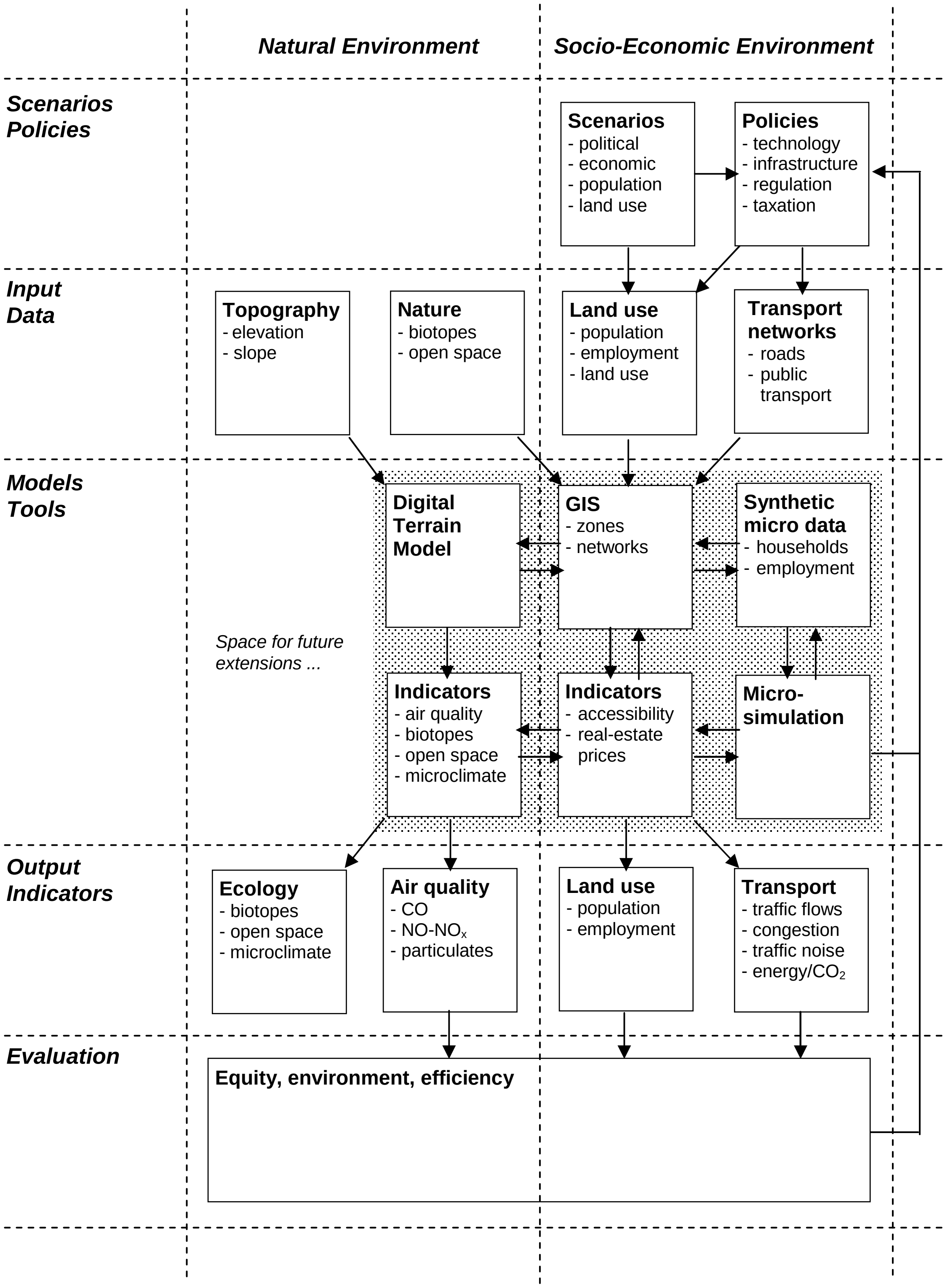

Fig. 7. The integrated microsimulation framework

Conclusions

This paper reviewed the impacts of recent advances in computer memory and speed and geographic information systems on urban spatial planning models and identified a general trend towards disaggregation in substance, space and time made possible by the new technological potential.

It argued that this would make urban models richer in behavioural content and more responsive to land use and travel demand management policies. The higher spatial and temporal resolution would make them also suitable to model micro-scale environmental phenomena such as air pollution and traffic noise. This would be an important prerequisite for using the models for the identification of more sustainable planning policies.

The paper illustrated this point by presenting two applications of disaggregate modelling: a method for spatial disaggregation of aggregate zonal data for the generation of a synthetic microdatabase and post-processing the results of aggregate models, a method particularly suited for data-poor environments, and a framework for an urban microsimulation model which permits the application of microscopic activity-based transport modelling to changes in the life cycle of households, individuals and firms and to decisions on residential and business location.

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