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Microsimulation of Urban Land Use

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Abstract

The project ILUMASS (Integrated Land-Use Modelling and Transportation System Simulation) aims at embedding a microscopic dynamic simulation model of urban traffic flows into a comprehensive model system incorporating both changes of land use and the resulting changes in transport demand. The land-use component of ILUMASS will be based on the land-use parts of an existing urban simulation model, but is to be microscopic like the transport parts of ILUMASS. Microsimulation modules will include models of demographic development, household formation, firm lifecycles, residential and non-residential construction, labour mobility on the regional labour market and household mobility on the regional housing market. These modules will be closely linked with the models of daily activity patterns and travel and goods movements modelled in the transport parts of ILUMASS developed by other partners of the project team. The design of the land-use model takes into account that the collection of individual micro data (i.e. data which because of their micro location can be associated with individual buildings or small groups of buildings) or the retrieval of individual micro data from administrative registers for planning purposes is neither possible nor, for privacy reasons, desirable. The land-use model therefore works with synthetic micro data which can be retrieved from generally accessible public data.

ILUMASS is a group project of institutes of the universities of Aachen, Bamberg, Dortmund, Cologne, and Wuppertal under the coordination of the Transport Research Institute of the German Aerospace Centre (DLR). Study region for tests and first applications of the model is the urban region of Dortmund. The common database is being compiled in co-operation with the City of Dortmund. After its completion the integrated model is to be used for assessing the impacts of potential transport and land-use policies for the new land-use plan of the city.

1. Introduction

There is growing awareness that the way of life practised in the most affluent countries of the world is not sustainable. People in the richest countries consume significantly more energy and other resources per capita than people in the poorest regions and by the same margin generate more greenhouse gases, noxious emissions and waste. This imbalance is aggravating due to the faster growth in income in the already richer regions and the subsequent changes in lifestyles, consumption, and travel patterns.

The causes of growing energy consumption and pollution by transport have a distinct spatial and urban dimension. With growing affluence and continuing low transport costs, urban residents choose more distant housing locations at the periphery of metropolitan areas to take advantage of better quality of life and lower land prices. Retail and service facilities and later workplaces in general follow and settle on greenfield sites with the effect that the proportion of car trips continues to grow at the expense of environment-friendly transport modes and that ever more open space is used for development.

All cities in Europe struggle with the problems of urban sprawl, yet mostly with little success. It is increasingly becoming clear that market forces will continue to lead to ever more dispersed, energy-wasteful urban settlement patterns. Land-use policies like the promotion of higher-density, mixed-use urban forms more suitable for public transport become necessary. But only a combination of land-use policies and transport policies promoting public transport and containing the private automobile can limit further urban dispersion and free metropolitan areas from their increasing auto-dependency. However, the necessary integration of land-use and transport planning is rarely achieved, and the complex interaction between land-use and transport policies is still poorly understood.

Today there is a new interest in integrated models of urban land use and transport provoked by the environmental debate. There is a growing awareness that market forces will continue to lead to ever more dispersed, energy-wasteful urban settlement patterns and that only a combination of land-use policies, such as the promotion of higher-density, mixed-use urban forms, and of transport policies to promote public transport and contain the automobile can free metropolitan areas from their increasing auto-dependency. In the United States and in Europe the number of integrated urban land-use transport models that can be used for assessing environmental impacts of land-use and transport policies is increasing (Wegener 1994, 1998; United States Environmental Protection Agency 2000). The ILUMASS project described in this paper is part of this development. The innovation of ILUMASS is that it is done completely by microsimulation.

This paper is organised in seven chapters. After the introduction an overview of the ILUMASS project is given. Next the advantages of microsimulation and the needed micro database are discussed. Chapter 5 shows examples of microsimulation modules to illustrate the functioning of this microscopic approach. Finally the future of land-use/transport/environment models is discussed.

2. Overview of the ILUMASS Project

The project ILUMASS (Integrated Land-Use Modelling And Transportation System Simulation) aims at embedding an existing microscopic dynamic simulation model of urban road traffic flows into a comprehensive model system incorporating both changes in land use and the resulting changes in transport demand. The project is funded by the German Federal Ministry of Education and Research and will last for three years. It is accomplished in corporation of six research institutes at the Universities of Aachen, Bamberg, Dortmund, Cologne, and Wuppertal and headed by Transport Research Institute of the German Aerospace Centre (DLR).

ILUMASS will work completely microscoptic, i.e. land-use changes and traffic flows are simulated by microsimulation. The land-use component is based on the land-use parts of the existing IRPUD Model (Wegener 1999). The ILUMASS project aims at developing, testing, and applying a new type of integrated urban land-use/ transport/environment (LTE) planning model. The interactions between activity and mobility patterns of single household members are represented. New lifestyles and work patterns such as part-time work, telework and teleshopping can be represented. The interactions between travel demand, car ownership, and residential and firm location as well as the interactions between land use, built form, and mobility behaviour are simulated. Furthermore the environmental impacts of transport such as traffic noise or exposure to air pollution are included. After its completion the integrated model is to be used for assessing the impacts of potential transport and land-use policies for the new land-use master plan of the city.

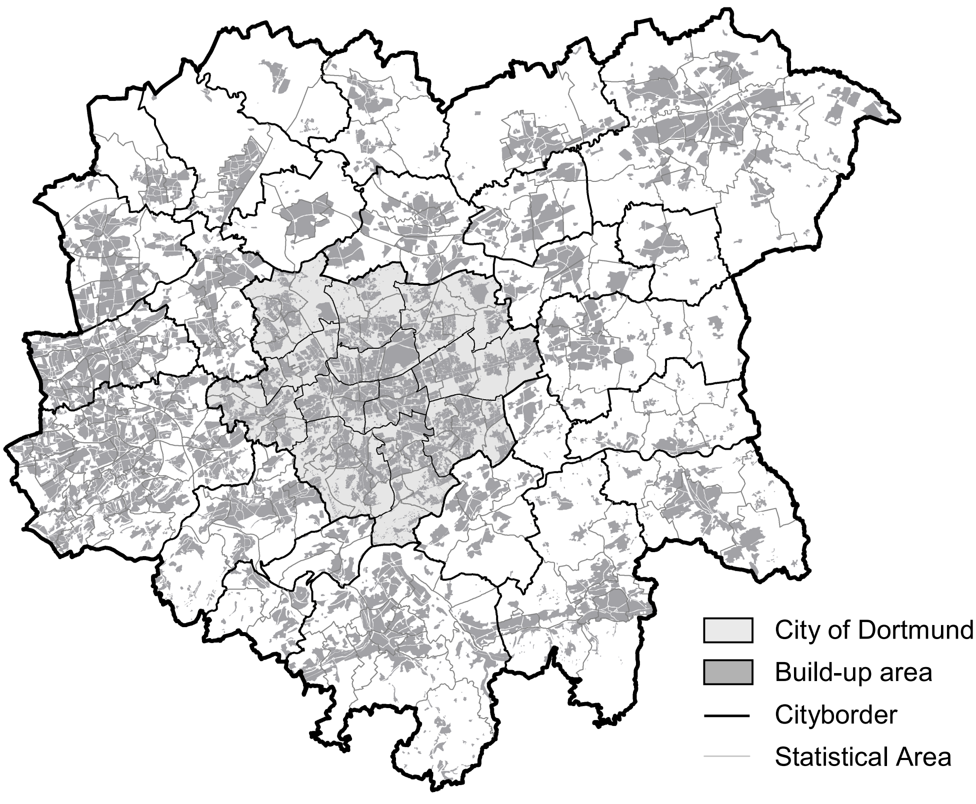

Figure 1. The study region Dortmund and its 25 surrounding communities

The study region for tests and first applications of the model is the urban region of Dortmund (Figure 1). The area consists of Dortmund and of its 25 surrounding communities. The area is subdivided by 246 statistical zones, so the microdata can be generated separately for every single statistical zone. However, even this spatial resolution is not sufficient for analysing environmental impacts such as air quality and traffic noise, which require a much higher resolution. Raster techniques are used to disaggregate zonal data to raster cells of 100 by 100 m size for the calculation of spatially disaggregate environmental and equity indicators. Figure 2 shows the detailed map of the city centre of Dortmund. A demonstration of the raster cells gives an idea about the size of the cells. There are about 200,000 raster cells to cover the study area.

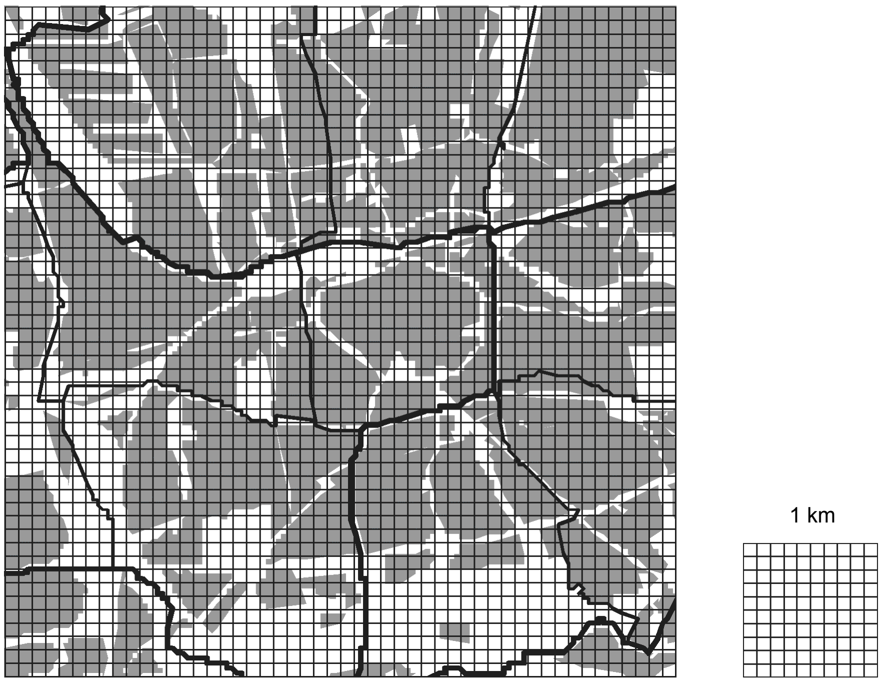

Figure 2. The Dortmund city centre with raster cells

3. Advantages of Microsimulation

Today there is a new interest in integrated models of urban land use and transport provoked by the environmental debate. However, the sustainability issue, together with new technological developments and new planning policies, also presents new challenges to urban modelling. New intermodal travel alternatives such as park-and-ride and kiss-and-ride, new forms of paratransit such as car-sharing, shared taxis or busses on demand and new lifestyles 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 and transport policies, and this requires small area forecasts of emissions from stationary and mobile sources as well as of immissions 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 lifestyles 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.

These considerations suggest a fundamentally new organisation of urban models based on a microscopic view of urban change. The method for this new type of model is Monte Carlo microsimulation. Basically microsimulation is the reproduction of a macro process by many micro processes. Single events of distinct actors are the basic building block of microsimulation. No deterministic assertions that are valid with certainty can be made. Instead probabilistic assertions that are valid only with probability are made about events.

Microsimulation models aim at reproducing human behaviour at the individual level, i.e. how individuals choose between options following their perceptions, preferences and habits subject to constraints, such as uncertainty, lack of information and limits in disposable time and money. Microsimulation was first used in social science applications in the 1960s, yet applications in a spatial context remained occasional experiments without deeper impact though covering a wide range of phenomena such as spatial diffusion, urban development, transport behaviour, demographic and household dynamics and housing choice. Only recently microsimulation has found new interest because of its flexibility to model processes that cannot be modelled in the aggregate. Today there are several microsimulation models of urban land use and transport under development in North America: the California Urban Futures (CUF) Model at the University of California at Berkeley (Landis and Zhang 1998a, 1998b), the Integrated Land Use, Transport and Environment (ILUTE) model at Canadian universities under the leadership of the University of Toronto (Miller 2001), the Urban Simulation (UrbanSim) model at the University of Washington, Seattle (Waddell 2000), and the 'second-generation' model of the Transport and Land-Use Model Integration Program (TLUMIP) of the Department of Transportation of the State of Oregon, USA. There are no efforts of camparable size in Europe. There are a few national projects, such as the Learning-Based Transportation Oriented Simulations System (ALBATROSS) of Dutch universities (Arentze and Timmermans 2000) or the Integrated Land-Use Modelling and Transportation System Simulation (ILUMASS) in Germany described here.

Probably the most advanced area of application of microsimulation in urban models is travel modelling. 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. 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. Activity-based transport models are now under development in several countries and are generally considered to be the state-of-the-art transport forecasting model of the future. The most prominent example is the very large Transportation Simulation System (TRANSIMS) programme of the US Department of Transportation.

There are three kinds of process that can be distinguished in microsimulation (Wegener et al. 1986):

- *Choices*. A choice stands for 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 workplace. 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.

- *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, 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.

- *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. Policies usually are set by the user of the model in order to run different scenarios

One of the most important underlying behavioural theories is represented in the Binomial or the Multinomial Logit Model (Domencich and McFadden 1975). This approach generates a distribution of probabilities, giving a higher likelihood to more attractive alternatives. The Binomial Logit Model represents a decision between two alternatives. A Multinomial Logit Model serves to simulate decisions between several options; with increasing attractiveness the probability to select this alternative increases exponentially. With a Logit Model decisions are represented under uncertainty and under limited information. Decisions are not treated as an optimum with utility maximisation of each household, but a systematic deviation from the optimum is modelled. This approach is assumed to simulate decisions more realistically.

4. Micro Database

The collection of individual micro data, i.e. data that can be associated with single buildings, or the retrieval of individual micro data from administrative registers is neither allowed in Germany nor desirable for privacy reasons. Therefore the model will work with synthetic micro data which can be retrieved from general accessible aggregate data. Results of the model will be published only in aggregated form as well. In order to accomplish this restriction, aggregate socio-economic data have to be disaggregated by biproportional and multiproportional procedures. By means of additional information like digital land-use plots or aerial photographs synthetic micro data is generated and located, which are statistically equivalent with the aggregate input data.

The synthetic population represents individual actors of the model in form of households and household members. Each household has certain characteristics like household size, income, number of cars, and address. In addition, each person is simulated by characteristics such as age, sex, nationality, and employment. These agents are assigned activities they accomplish in a day. They might go to work, go to school, shop or go to the doctor. They choose a transport mode and so produce traffic flows. In the long run, households might decide to move and so affect land use.

The synthetic businesses represent the employers in the model. Businesses are described by their industry, number of employees, number of vehicles, and location within the study region. Public amenities are a special case of businesses. They include institutions like kindergarten, schools, universities or museums. They affect land use by the foundation, relocation or shutdown of businesses.

The micro database contains residential and non-residential buildings. Several features are associated with each dwelling: building type, size, quality and price. Every dwelling has a raster cell as a micro location. Raster cells are used as addresses for the microsimulation. To 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 consideration, 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. Figure 3 illustrates the two steps for a simple example (Spiekermann and Wegener 1999, 2000).

For the disaggregation of land-use data to raster data GIS techniques are used. Vector-based geographic information systems store land-use data as attributes of polygons. To convert polygon land-use data into raster data, the following three 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 raster representation by using a point-to-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.

- For each activity to be disaggregated weights are assigned to each land-use category, and 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 that cell is the address of one element of the zonal activity. Cumulating the weights over the cells of a zone yields the 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 is a raster representation of the distribution of the activity within the zone.

Figure 4 visualises the disaggregate database of the city of Dortmund in 3D form. The 3D plot in part (a) shows the spatial distribution of residences in Dortmund. One can see the high-density neighbourhood of the inner city and the low-density neighbourhoods of the inner suburbs in which there are only few high-rise housing areas. The 3D plot in part (b) shoes the locations of workplaces. Compared with residences, workplaces are much more centralised in the CBD (central business district) and the inner city and in the subcentres of the polycentric suburban area. If residences and workplaces are interpreted as origins and destinations of work trips, the spatial distribution of work trips can also be shown. This is done in the 3D plot in Figure 4 in part (c). Work trips are bundled in corridors toward the CBD and the inner city, some minor peaks can be found at suburban centres.

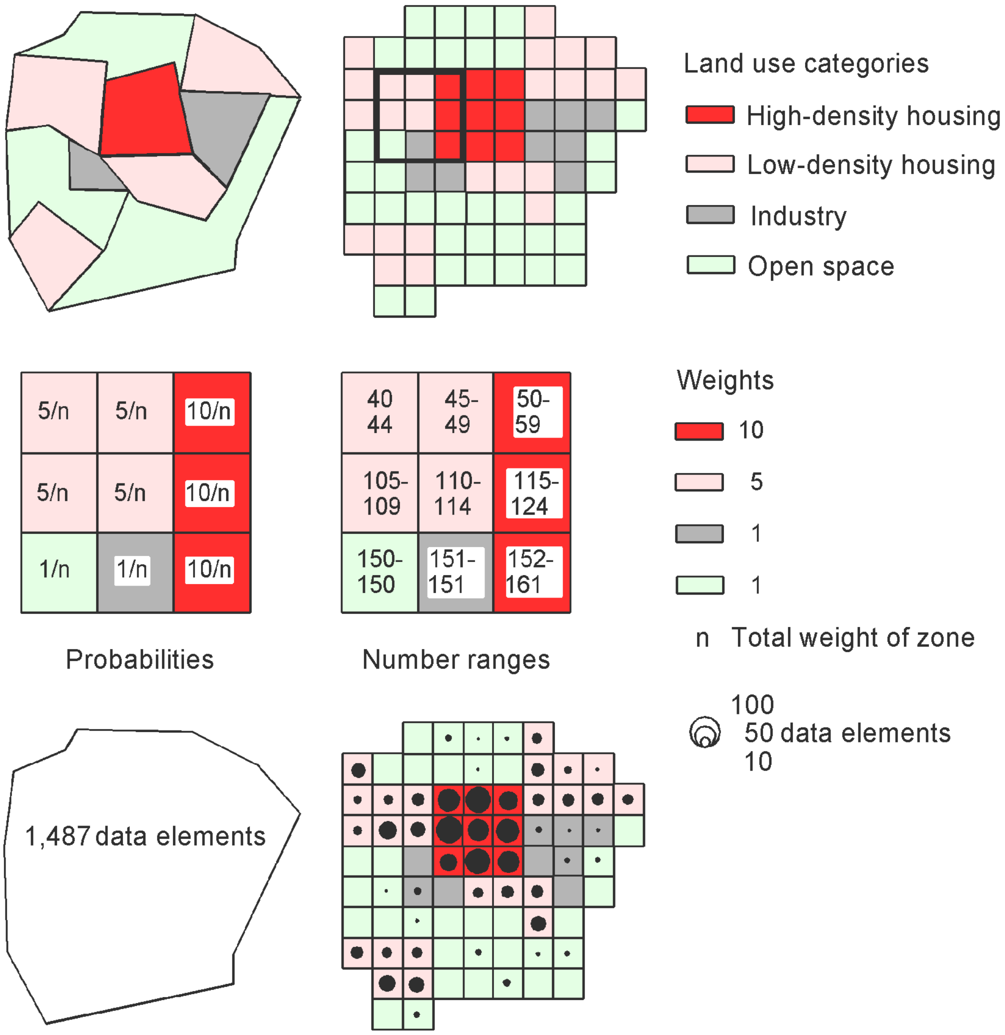

Figure 3. Disaggregation of zonal to raster data (Spiekermann and Wegener 2000: 48)

a)

b)

c)

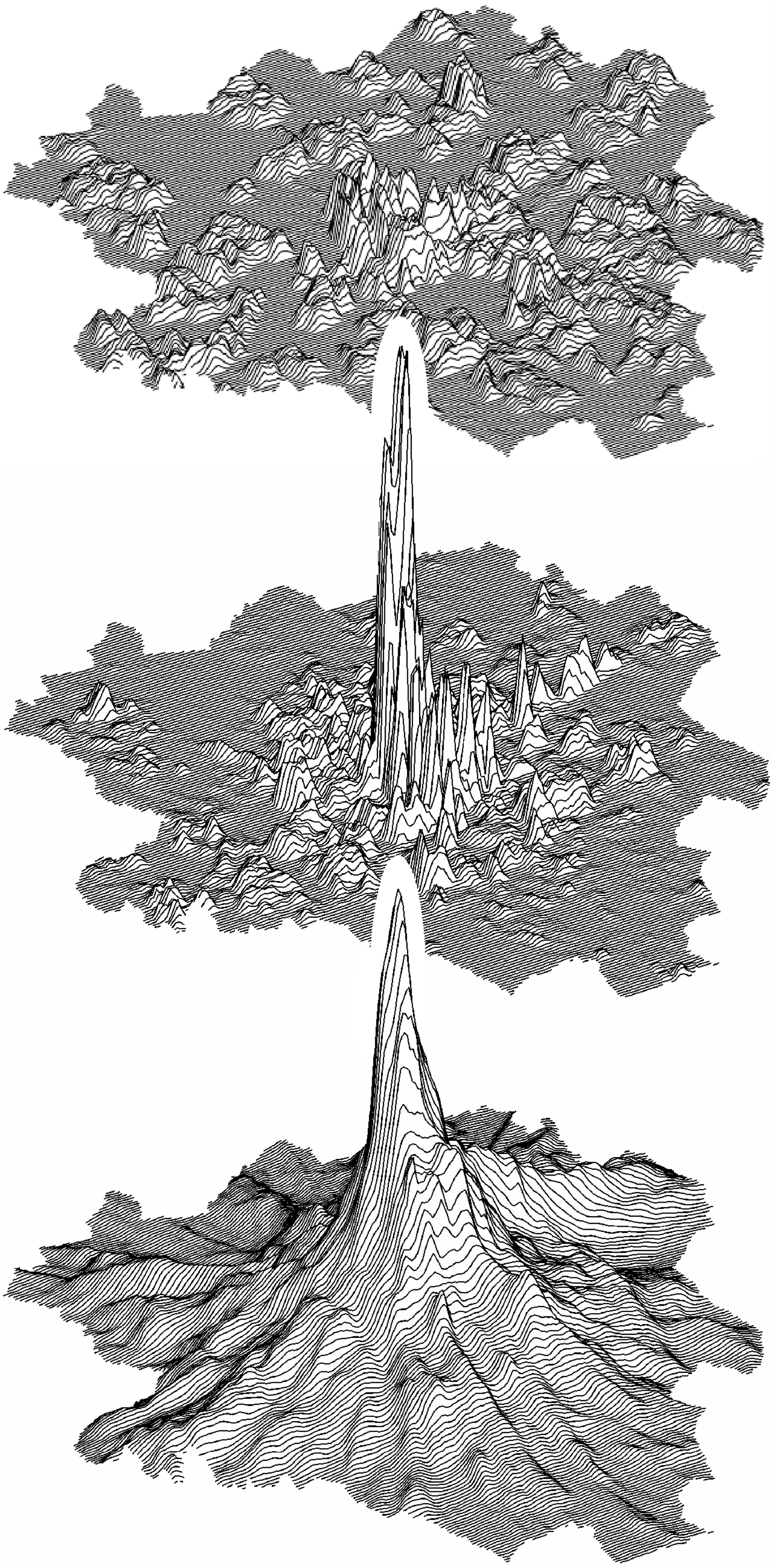

Figure 4. Three-dimensional representation of (a) residences, (b) workplaces and (c) work trips in Dortmund (Spiekermann and Wegener 2000: 50)

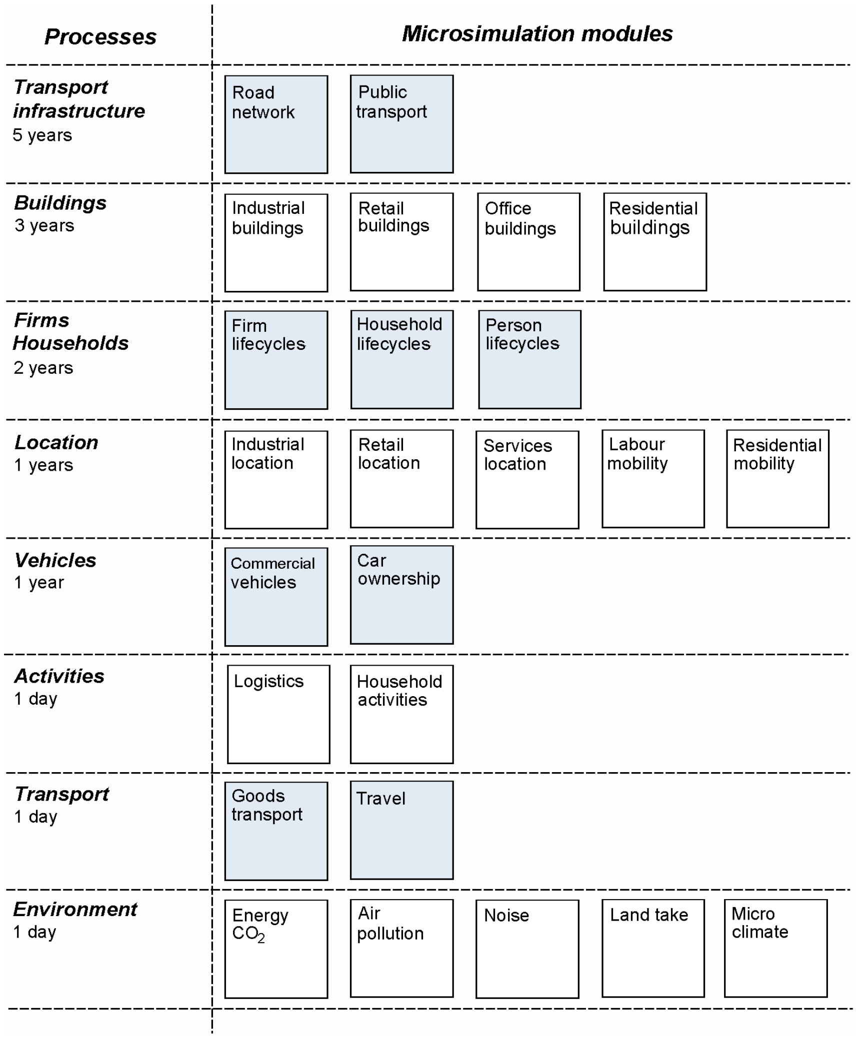

Figure 5. Urban change processes and microsimulation modules

5. Microsimulation Modules

The common elements of the simulation model include the philosophy and basic structure of the approach, the selection of base modules for microsimulation, the definition of data organisation and data interfaces and the definition of output indicators. Beyond these common elements, it is always possible to include further microsimulation modules. Co-ordination of the modelling work is facilitated by the strictly modular structure of the model. Each microsimulation module is a separate software procedure with defined input and output interfaces. A list of microsimulation modules ordered by increasing speed of change from slow to fast changes is presented in Figure 5:

- Transport infrastructure and buildings represent the slowest kind of change; their construction takes many years, and their lifespan is counted in decades.
- Firms and households have also lifecycles of several years but are easier established or dissolved.
- Firms and households change their location several times during their lifecycle yet even more frequently adjust their vehicle fleets to changing needs.
- Whereas all the above changes are counted in years, logistics and household activities change from hour to hour during a single day.

- The fastest urban processes are goods transport and travel. They adjust in response to events in a matter of minutes.
- Environmental processes partly reflect the effects of human activities without delay but partly have long-term consequences.

The microsimulation modules interact in various ways with each other. Figure 6 shows that the number of interactions between the microsimulation modules is enormous (and would be even larger if also indirect impacts were taken into account).

Change of ... causes / ... change of...	Road network	Public transport	Industrial buildings	Retail buildings	Office buildings	Residential buildings	Firm lifecycles	Household lifecycles	Person lifecycles	Industrial location	Retail location	Services location	Labour mobility	Residential mobility	Commercial vehicles	Car ownership	Logistics	Household activities	Goods transport	Travel	Energy, CO_2	Air pollution	Noise	Land take	Micro climate
Road network	●		●	●	●	●				●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Public transport		●											●	●		●		●		●	●	●	●	●	●
Industrial buildings			●							●											●	●	●	●	●
Retail buildings				●							●										●	●		●	●
Office buildings					●							●									●	●		●	●
Residential buildings						●								●							●	●		●	●
Firm lifecycles							●	●	●	●	●	●	●		●		●		●						
Household lifecycles						●		●	●					●		●		●		●					
Person lifecycles						●		●	●					●		●		●		●					
Industrial location			●							●		●	●	●	●		●	●	●	●					
Retail location				●							●	●	●	●	●		●	●	●	●					
Services location					●							●	●	●	●		●	●	●	●					
Labour mobility													●			●		●		●					
Residential mobility						●						●	●	●		●		●		●					
Commercial vehicles															●		●		●		●	●	●		
Car ownership						●							●	●		●		●		●	●	●	●		
Logistics															●		●		●						
Household activities													●	●		●		●		●					
Goods transport										●	●	●			●		●		●		●	●	●		●
Travel																●		●		●	●	●	●		●
Energy, CO_2			●	●	●	●															●				
Air pollution											●	●		●								●			
Noise											●	●		●									●		
Land take														●										●	
Micro climate														●											●

Figure 6. Interactions between microsimulation modules

Some of these interactions are highly delayed, i.e. take their time to work their way through the system. For instance, increasing demand for office space or housing will result in new office space or new housing only after several years because of long planning and construction periods. Other impacts are much faster. For instance, dwellings vacated by households enter the supply of available housing after a few weeks. Still other impacts are almost immediate, such as driver response to congestion. This variety of response speeds requires that the exchange of information between the microsimulation modules is very efficient. This is achieved by the common micro database.

The following two examples show how microsimulation can be applied to urban modelling:

- *Household Formation.* The household formation microsimulation module models the evolution of household attributes associating each household with a particular life style (Figure 7). In the household formation module the following household events are modelled simultaneously for households and household members: birth, ageing, death; new household, dissolution of household; marriage/divorce, cohabitation/separation, separation of child, person joins household; new job, retirement, unemployment; change of income. 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 simply as the result of the passage of time, i.e. as transitions (Wegener 1986). Typical transitions are 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 un-

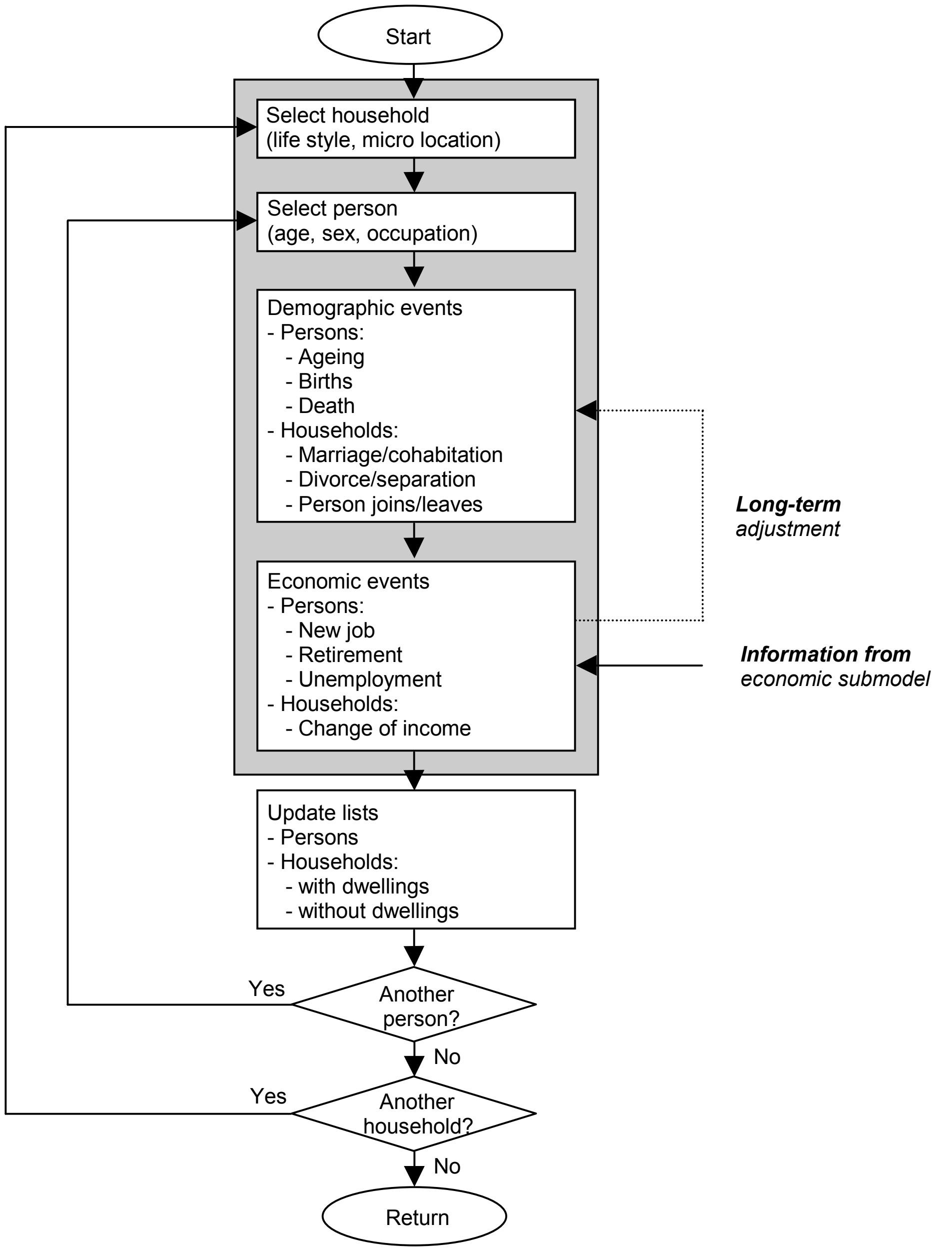

Figure 7. Microsimulation of household formation

employment are triggered by external events such as hiring or firing in the labour market represented in another part of the model not described here. 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 income expectations. The role of labour market expectations in shaping these choices is an area of considerable policy implication.

- *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). Dwellings are affected by ageing and by decisions on new construction, upgrading and demolition modelled in other modules not described in this context. The housing choice model is a Monte Carlo microsimulation of transactions in the housing market. A

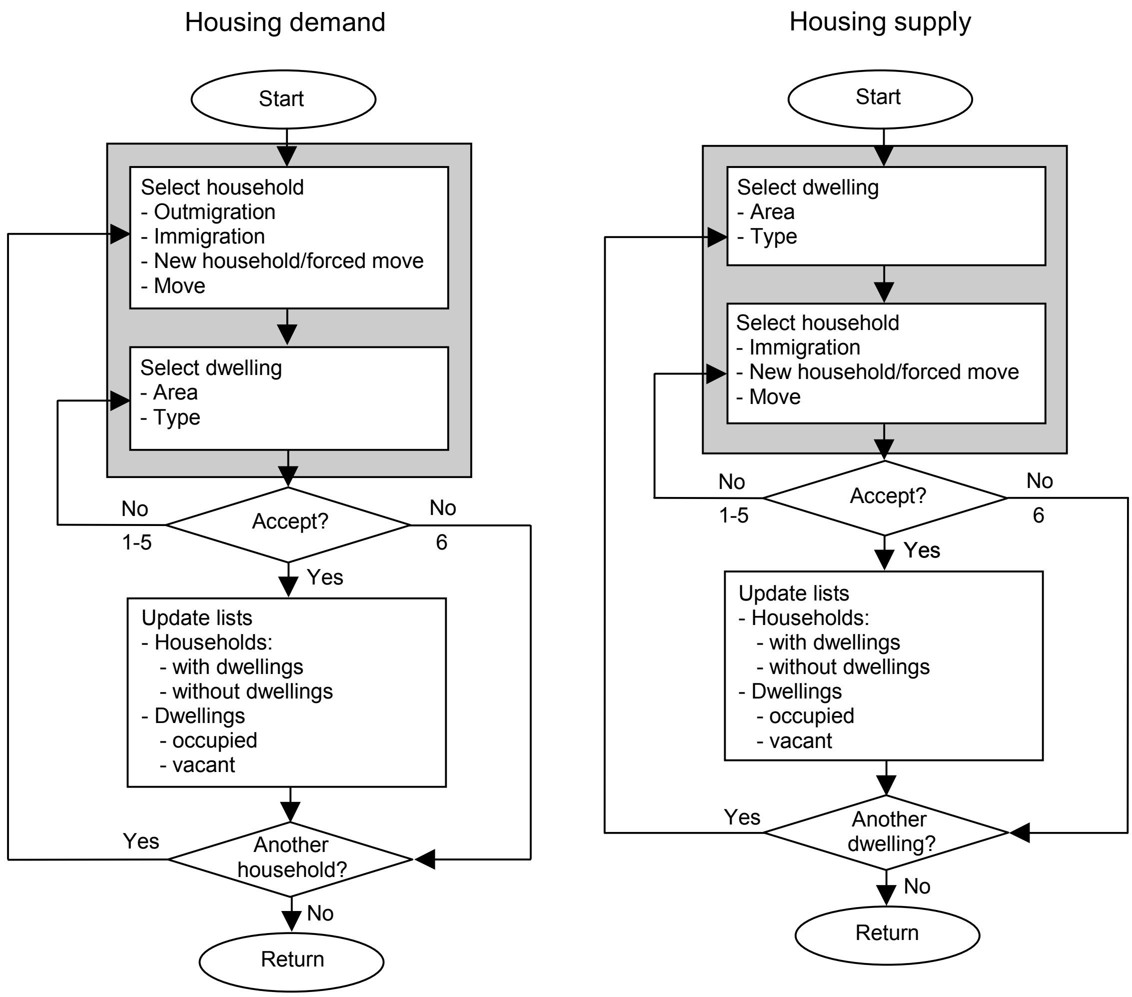

Figure 8. Microsimulation of housing choice

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 (Figure 8): households looking for a dwelling ('dwelling wanted') and landlords looking for tenants or buyers ('dwelling for rent or sale'). The household looking for a dwelling behaves as a satisficer, i.e. it accepts a 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. to 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. 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.

Figure 9 shows the relationship between the microsimulation modules (represented by the box 'Microsimulation') and the other parts of the modelling process. The first and second rows of boxes show the different kinds of input. The boxes labelled 'GIS' and 'Synthetic micro data' represent the pre-processing steps to generate the spatial micro database. The boxes labelled 'Output Indicators' represent modules calculating indicator values for raster cells, such as socio-economic, traffic and accessibility indicators as well as emissions, exposure to traffic noise and air pollution. Environmental modules will include modules calculating energy consumption, greenhouse gas emissions (CO_2), traffic noise and gaseous emissions as well as exposure of population of different socio-economic groups to noise and air pollution and impacts of transport infrastructure on open space, biodiversity and microclimate. Future project extensions might be developed that model the natural environment with more detail, such as non-local air movement models with photo-chemical reaction, or hydrological models.

6. The Future of Land-Use/Transport/Environment Simulation Models

The results of the policy scenarios will contribute to the knowledge about feasible and successful policies and policy packages to achieve sustainable urban transport. The definition of policy scenarios together with local planners will be a thorough test of the policy relevance of the models. Scenarios might cover infrastructure changes like new construction, upgrading, or demolitions. Various transport policies like car pricing, alternative tax structures or rail fare changes can be simulated as well.

The presented model under development will be completely disaggregate dealing with micro locations and movements of individual agents and destinations (households, firms and persons) on a surface of pixel-like grid cells combining for the first time a microscopic land-use model with a microscopic activity-based travel demand model and microscopic environmental impact models in one unified modelling framework. It remains to be asked whether the movement towards ultimate disaggregation in content, space and time is the right way to go.

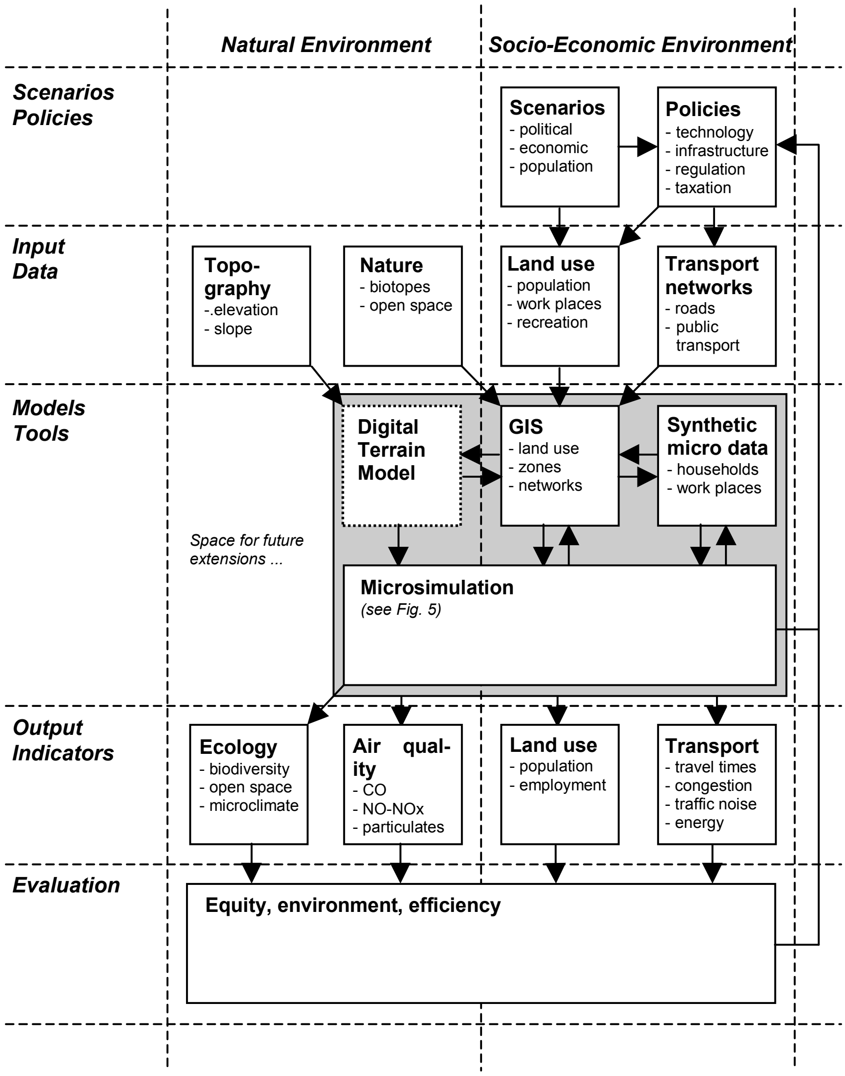

Figure 9. The model framework

From a technical point of view, the prospects are excellent. More powerful computers will remove former barriers to increasing the spatial, temporal and substantive resolution of models. The wealth of publicly available high-resolution spatial data will reduce aggregation errors in spatial models. Geographic information systems will become the mainstream data organisation of urban models. Spatial disaggregation of land-use and transport network data in raster GIS will permit the linkage between land-use transport models and dispersion (emission-immission) air quality and noise propagation models. Multiple representation of spatial data in raster and vector GIS will combine the advantages of spatial disaggregation (raster) and efficient network algorithms (vector). It will be possible to replace aggregate probabilistic approaches (e.g. entropy maximising) by disaggregate stochastic (microsimulation) approaches.

Miller et al. (1998) presented a matrix in which they charted the past and future evolution of urban land-use transport models. Figure 10 is an adaptation in which a sixth row L6 was added. The rows of the matrix correspond to different levels of modelling capability from pure travel models having no land-use model to activity-based land-use models using microsimulation. In a similar way, the columns of the matrix represent different levels of travel demand modelling capability from travel models considering only roads and auto travel to multimodal activity-based travel models using microsimulation.

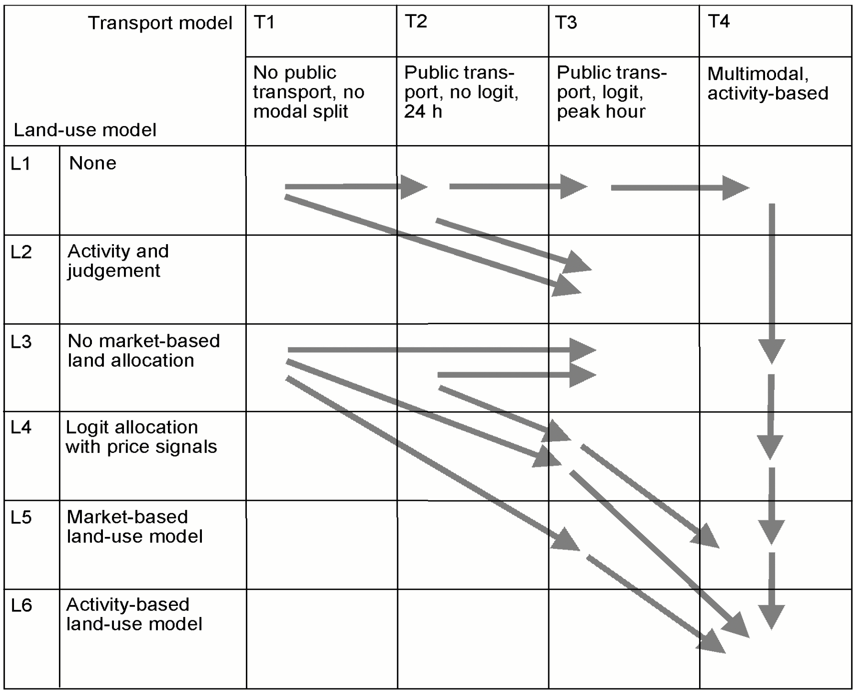

Figure 10. Evolution of urban land use transport models (adapted from Miller et al. 1998)

Each cell of the matrix therefore represents a land-use transport modelling combination, and the arrows indicate incremental paths of model evolution. The matrix could be made three-dimensional by adding the environment dimension which, as it has been shown, also provides strong reasons for making urban models more disaggregate. The question is what will happen with urban modelling when the lower right cell, the fully disaggregate activity-based model of land use, transport and the environment, as it is intended of the model presented in this paper, will have been achieved.

There are voices in the ongoing debate about microsimulation in urban modelling suggesting that the lower right cell may not be the ultimate destination of model evolution. The price to be paid for all-out disaggregation in terms of data collection and computing effort may be too high for the level of generalisation at which the results could be of interest for policy making (Harris 2001). Disaggregate models may be suitable for modelling individual bottom-up behaviour but are incapable of taking account of larger macro trends which may arise from long-term socio-economic developments or from the interaction with other regions (Torrens 2001).

These considerations deserve careful attention. Their most likely consequence is that integrated urban models of the future will be multi-level in scope, space and time, i.e. model macro socio-economic trends at the level of the urban region at large (e.g. in multi-regional socio-economic models), meso developments at the level of urban districts or neighbourhoods (e.g. accessibility or attractiveness indicators) and individual behaviour at the micro, i.e. raster or parcel level. The challenge would be to capture the linkages between the levels in both downward and upward direction, i.e. to model how macro and meso developments influence micro behaviour and how individual behaviour accumulates to emergent patterns of collective behaviour.

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