CHAPTER FOUR

Freedom from the Tyranny of Zones: Towards New GIS-Based Spatial Models

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4.1 INTRODUCTION

Pre-GIS spatial models get their spatial dimension through a zonal system. It is assumed that all attributes of a zone are uniformly spatially distributed throughout the zone. Spatial interaction between zones is established via networks that are linked to centroids of the zones. Zone-based spatial models do not take account of topological relationships and ignore that socio-economic activities and their impacts, e.g. 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*., 1993; Fisher and Langford, 1995). The captiveness of spatial modelling in the straitjacket of zonal systems is the 'tyranny of zones'.

For instance, most existing land use models lack the spatial resolution necessary to represent other environmental phenomena than energy consumption or CO_2 emissions. In particular emission-immission algorithms such as air dispersion, noise propagation and surface and ground water flows, but also micro climate analysis, require a much higher spatial resolution than large zones in which the internal distribution of activities and land uses is not known: Air distribution models typically work with raster data of emission sources and topographic features such as elevation and surface characteristics such as green space, built-up area, high-rise buildings and the like. 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. Micro climate analysis depends on small-scale mapping of green spaces and built-up areas and their features. In all four cases the information needed is *configurational*. This implies that not only the *attributes* of the components of the modelled system such as quantity or cost are of interest but also their physical *micro location*. This suggests a fundamentally new organisation of urban land use transport environment (LTE) models based on a microscopic view of urban change processes (Wegener and Spiekermann, 1996a).

This is where geographic information systems (GIS) come into play. A combination of raster and vector representations of spatial elements as it is possible in GIS might lead to spatially disaggregate models that are able to overcome the disadvantages of zonal models. Using spatial interpolation techniques, zonal data can be disaggregated from polygons to pixels to allow the calculation of micro-scale indicators such as accessibility or air pollution. The vector representation of transport networks allows the application of efficient network algorithms from aggregate transport models such as minimum path search, mode and route choice and equilibrium assignment. The combination of raster and vector representations facilitates activity-based microsimulation of both location and mobility in an integrated and consistent way (Wegener and Spiekermann, 1996a).

Chapter 4 in Fotheringham, A.S., Wegener, M., Eds. (2000): *Spatial Models and GIS: New Potential and New Models*. GISDATA 7. London: Taylor & Francis, 45-61.

4.2 LINKING MICROSIMULATION AND GIS

The modules and decision functions of a microsimulation model require disaggregate spatial data. Geographic information systems (GIS) offer data structures which efficiently link coordinate and attribute data. There is an implicit affinity between microanalytic methods of spatial research and the spatial representation of point data in GIS. Even where no micro data are available, GIS can be used to generate a probabilistic disaggregate spatial data base (Spiekermann and Wegener, 1993b; see also Bracken and Martin, 1989, 1995; and Martin and Bracken, 1991). There are four fields in which GIS can support micro techniques of analysis and modelling (see Figure 4.1):

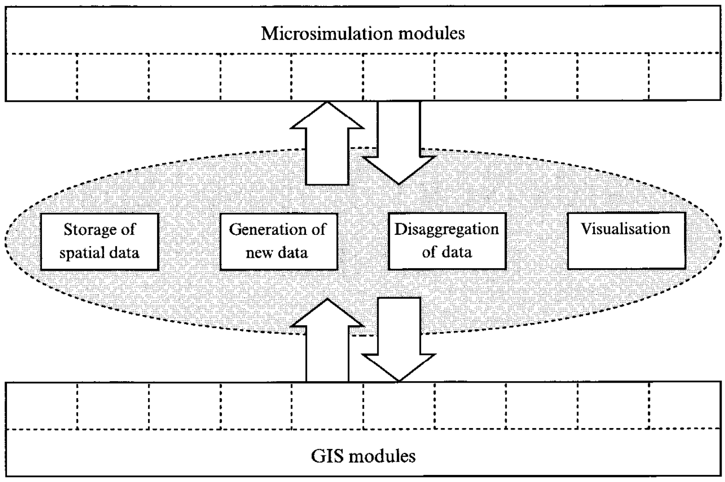


Figure 4.1 Linking microsimulation and GIS.

- *Storage of spatial data*. There is a strong similarity between the storage of individual data required for microsimulation and the structure of point coverages of GIS. In an integrated system of microsimulation modules a GIS data base may therefore be efficient for analysis and modelling.
- *Generation of new data*. GIS may be used to create new data for microsimulation that were not available before. This data can be derived using analytical tools of GIS such as overlay or buffering.
- *Disaggregation of data*. Most available spatial data are aggregate zonal data. Microsimulation requires individual, spatially disaggregate data. If micro data are not available, GIS with appropriate microsimulation algorithms can generate a probabilistic disaggregate spatial data base. A method for generating synthetic micro data is presented in the next section.
- *Visualisation*. Microsimulation and GIS can be combined to graphically display input data and intermediate and final results as well as through animation visualise the evolution of spatial systems over time.

4.3 SPATIAL DISAGGREGATION OF ZONAL DATA

Spatial microsimulation models require the exact location of the modelled activities, i.e. point addresses as input. However, most available data are spatially aggregate. To overcome this, raster cells or pixels are used as addresses for microsimulation. 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 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 4.2 illustrates the two steps for a simple example.

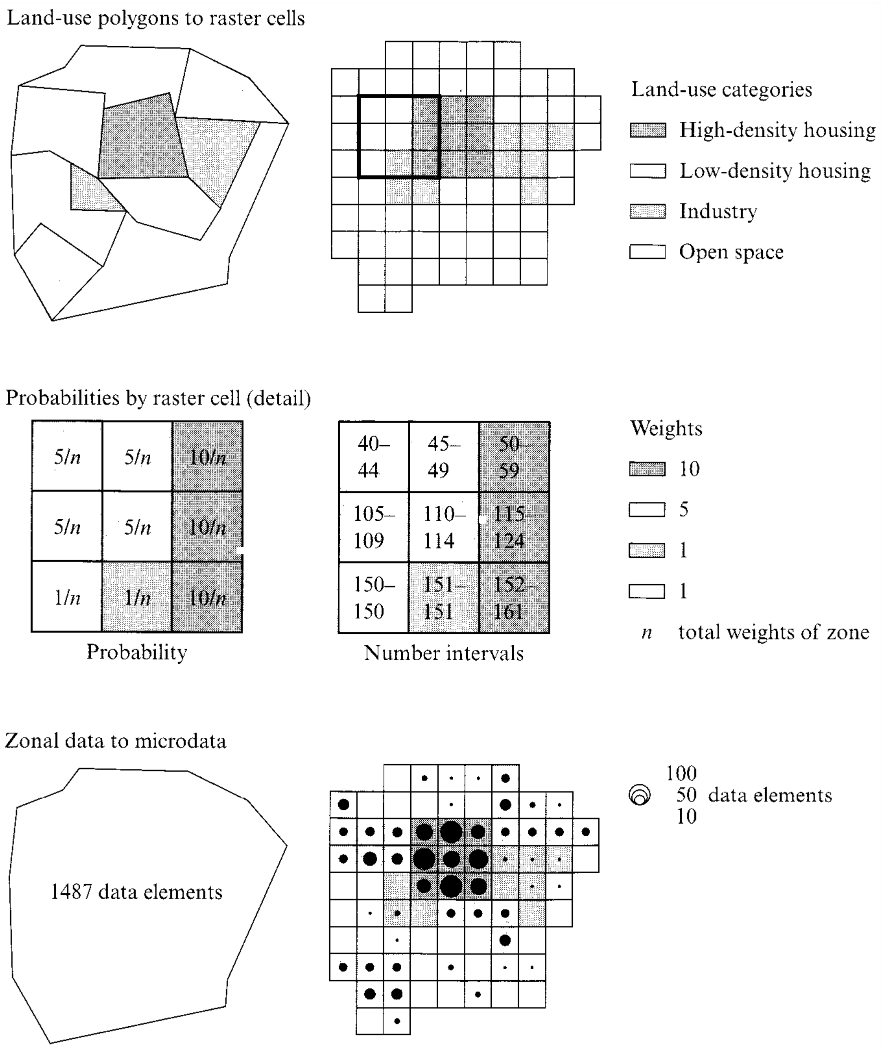


Figure 4.2 Disaggregation of zonal data to raster cells.

Vector-based GIS record land use data as attributes of polygons. If the GIS software has no option for converting a polygon coverage into a raster representation, 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 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. 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 for that cell to 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.

Figures 4.3 to 4.5 demonstrate how this method was used to disaggregate population and employment in Dortmund. Land use, population and employment data were available for 170 statistical districts. Figure 4.3 shows the digitised land use map consisting of 2,600 parcels classified by twelve land use categories (collapsed to three categories for better reproduction here). Figure 4.4 shows the spatial disaggregation of population and employment after the disaggregation. The width of the cells used was 50 m, i.e. every pixel on the map represents a square of 50x50 m. The upper part of the figure shows residences, the lower part jobs. The distribution of the different activities visualises the urban structure of Dortmund and is consistent with the land use pattern of Figure 4.3.

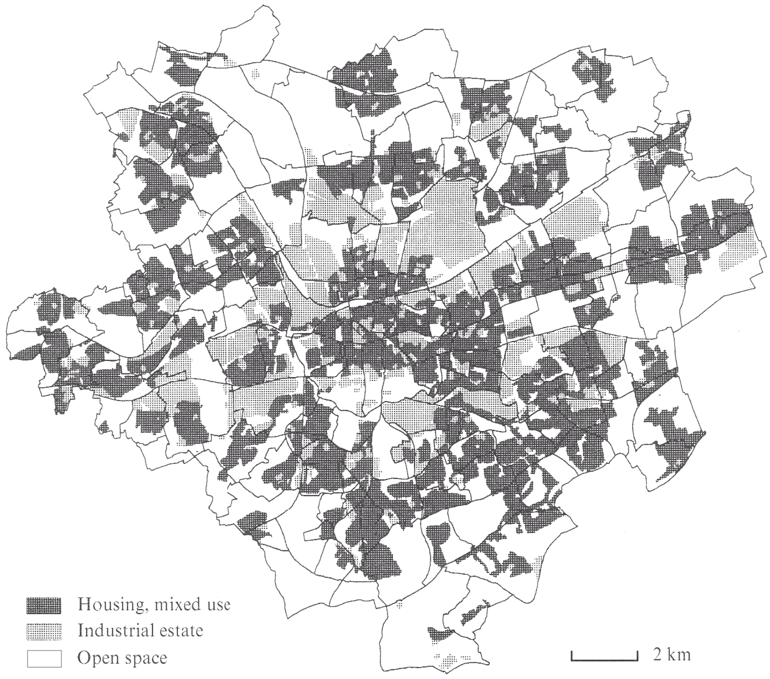


Figure 4.3 Land use in Dortmund by parcel.

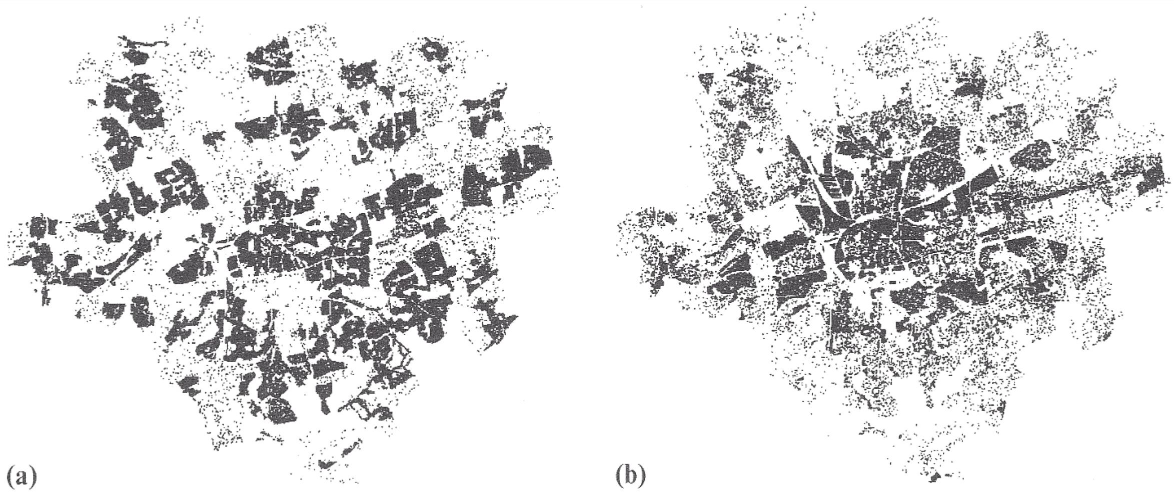


Figure 4.4 Raster representation of (a) residences and (b) workplaces in Dortmund.

Figures 4.5 visualises the disaggregate data base in three-dimensional form. The 3D plot at the top shows the spatial distribution of residences in Dortmund. One can see the high-density neighbourhoods 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 the centre shows the locations of work places. Compared with residences work places are much more centralised in the CBD and the inner city and in the subcentres of the polycentric suburban area. If residences and work places are interpreted as origins and destinations of work trips, also the spatial distribution of work trips can be shown. This is done in the 3D plot at the bottom of Figure 4.5. Work trips are bundled in corridors towards the CBD and the inner city, some minor peaks can be found at suburban centres.

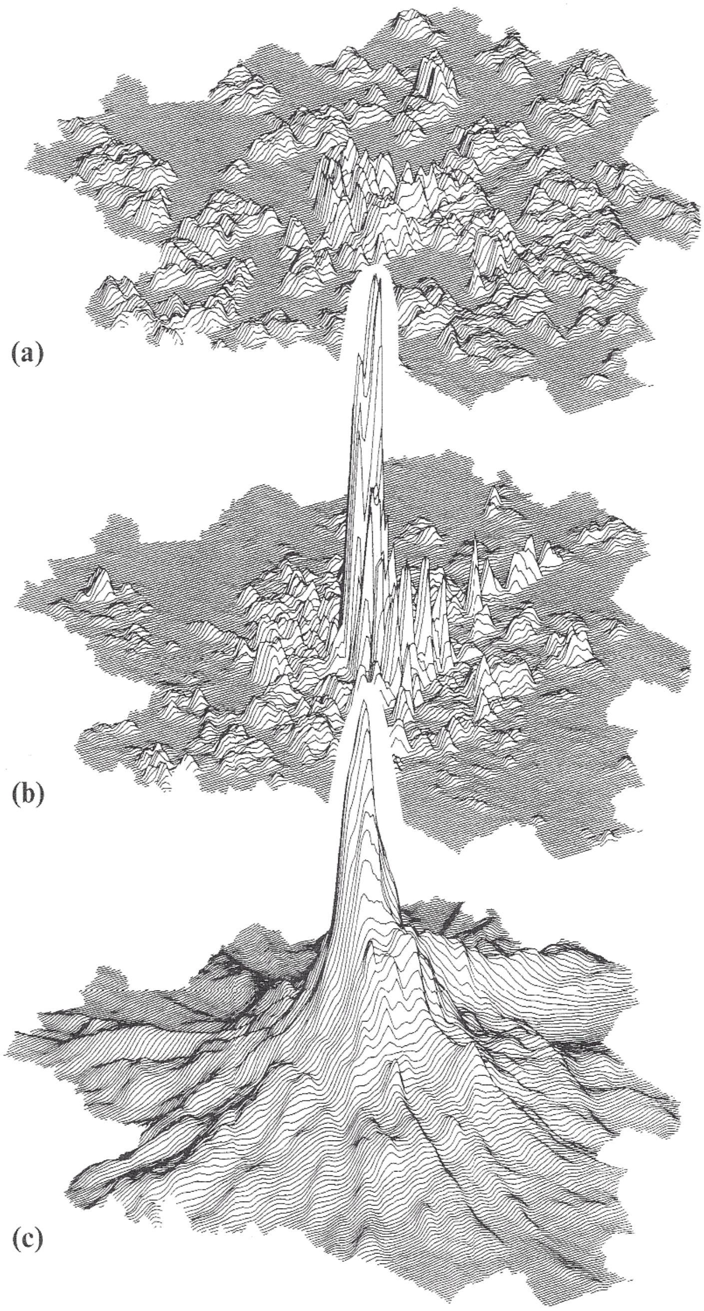


Figure 4.5 Three-dimensional representation of (a) residences and (b) workplaces and (c) work trips in Dortmund.

To correspond to the disaggregate representation of activities, the transport network was coded with great detail. Figure 4.6 shows the road and public transport networks of the Dortmund metropolitan area (with the built-up area superimposed over the road network). There are about 6,200 road links and about 5,900 public transport links and about 3,900 public transport stops. Public transport lines were coded as a sequence of stops with travel times between them. The cycling and walking networks are synthetically derived from the above networks with similar detail.

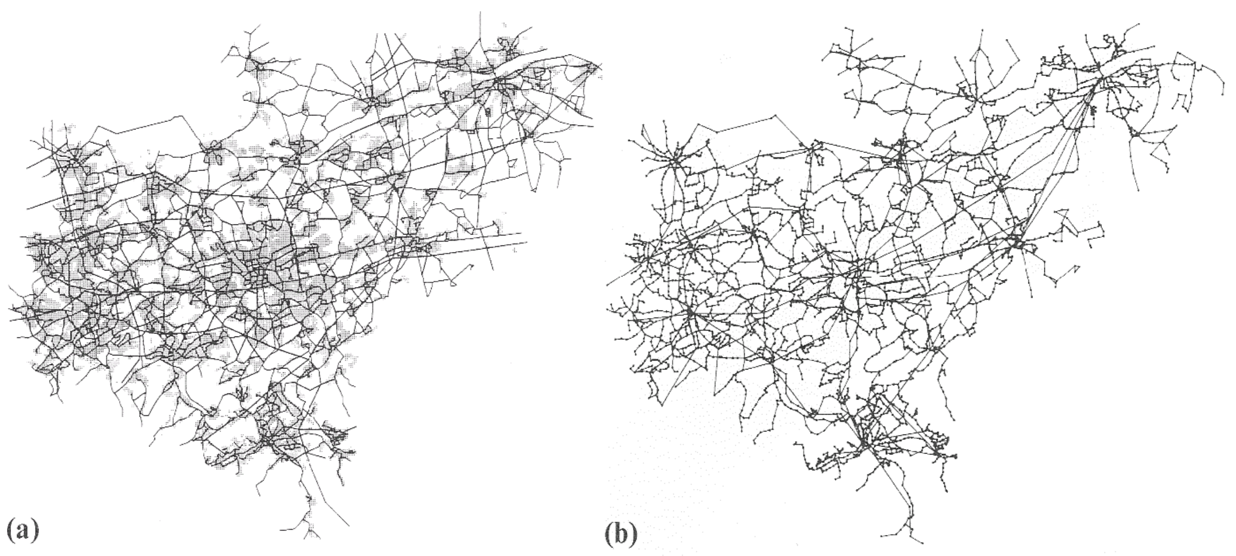


Figure 4.6 (a) Road and (b) public transport networks in the Dortmund metropolitan region.

The combination of the raster representation of activities and the vector representation of the transport network provides a powerful data organisation for the microsimulation 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 collective travel such as bike-and-ride, kiss-and-ride, park-and-ride or various forms of vehicle-sharing.

4.4 GIS-BASED MICROSIMULATION: TWO EXAMPLES

This chapter presents the methodology and results of two explorative studies applying GIS-based microsimulation at the urban and at the European scale. The first example uses a simple rule-based model of travel decisions to assess the pooling potential of urban work trips. The second example uses a gravity model to derive accessibility indicators for trans-European networks. The focus is on the integration of GIS-functionality into the models and in particular on the combination of raster and vector representations of zonal data and networks in order to demonstrate that by using this combination issues can be addressed that could not be dealt with before.

4.4.1 Car pooling and energy consumption

There exists a wide range of potential measures to reduce automobile commuter traffic. However, the joint use of vehicles such as cars, vans and minibuses, group taxis or other, more flexible forms of public transport, is only occasionally examined as a solution. In order to explore the potential of these forms of collective travel, one needs to know the microscopic, small-scale location of residences and workplaces and the resulting spatially disaggregate transport demand in the metropolitan region. This information is, however, not available. So there is no clear knowledge about the theoretical potential for energy conservation through vehicle sharing. This section summarises a study in which the theoretical pooling potential of work trips was investigated for the metropolitan region of Dortmund in Germany (Spiekermann and Wegener, 1992, 1993a).

The first step of the study was the generation of a disaggregate spatial data base of work trip origins and destinations of more than 210,000 work trips from aggregate census data. This step was presented as an example in the previous section. On the basis of these origins and destinations the microsimulation model calculates all possible pooling constellations of work trips and selects the most reasonable using criteria such as minimum detour of commuters or maximum passengers.

The criterion for whether two commuters can be pooled is whether they live in the same neighbourhood and/or work in the same area and travel at approximately the same time. If these conditions are satisfied, they can share a vehicle. Two kinds of pooling of work trips are distinguished (see Figure 4.7):

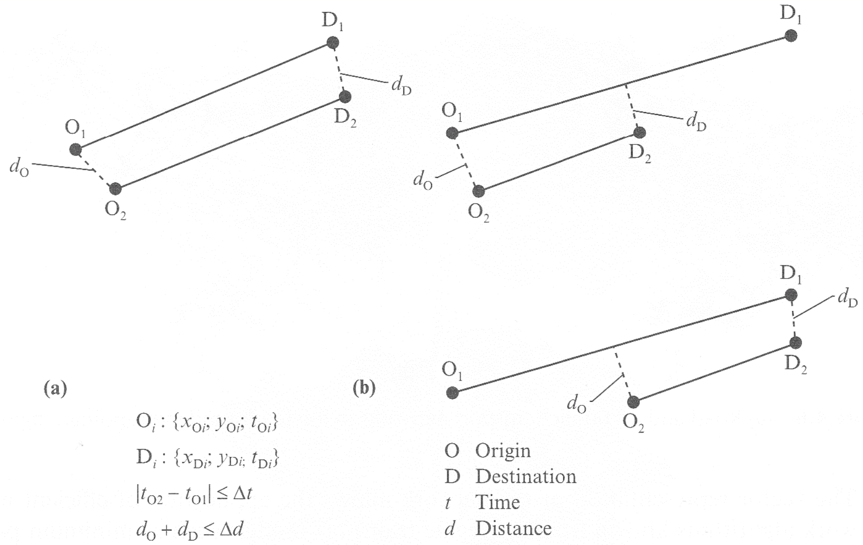


Figure 4.7 Criteria for a trip pooling. (a) Total trips; (b) parts of a trip.

- *Pooling on the whole trip*. Work trips can be pooled on the whole trip if origin, destination and departure time are similar. In this case all commuters of a pool stay together over the whole distance.
- *Pooling on parts of the trip*. Two work trips can be pooled on parts of the trip if either origin or destination and the departure time are similar and the shorter one of the two trips begins or ends along the route of the longer one.

In order to operationalise this, some definitions on what is spatial and temporal similarity are necessary. The definitions are that commuters are willing to adjust their departure time by a certain time interval Δt (15 or 30 minutes) and accept a maximum walking distance Δd (500 or 1,000 m) in order to join a car pool. If a work trip has a total length below Δd, it will not be pooled; the commuter is expected to walk to and from the job. These conditions are also applied if more than two work trips are to be pooled.

All work trips are analysed using the above criteria. This means that each work trip has to be compared with all other work trips with respect to spatial and temporal similarity. Each commuter is considered a potential driver, and all other commuters meeting the criteria are recorded as potential passengers. For example, the left part of Figure 4.8 shows commuter 33333 (white arrow) and all possible passengers (black arrows). In order to minimise computation time, for each commuter a search field for finding potential passengers was defined (dotted line). Depending on the combination of criteria, between three and 22 million pairs of commuters are possible. For instance, if Δd = 1,000 m and Δt = 30 minutes, every potential passenger can choose between more than a hundred drivers on average. The right part of Figure 4.8 shows commuter 33333 and potential drivers.

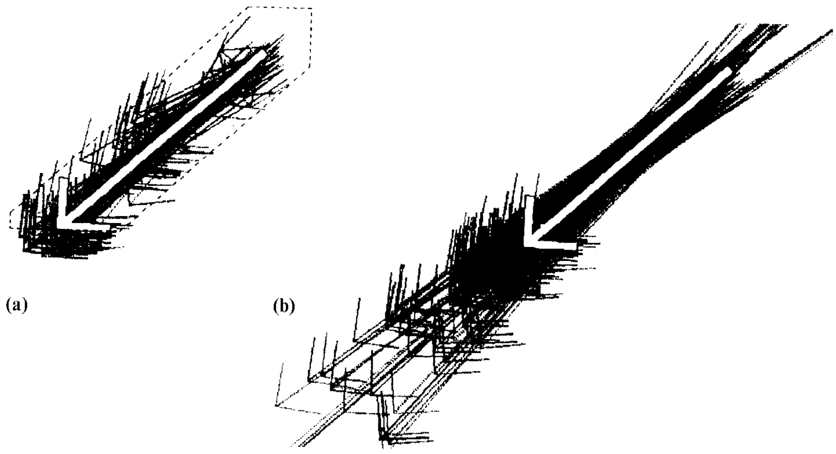


Figure 4.8 Commuter 33333 (white arrow). (a) Potential passengers, (b) potential drivers.

Obviously a commuter can be a passenger of one driver only. But which of the available pools should he or she join? In order to model the choice decision of passengers, two different criteria are used:

- If the passenger acts rationally, he or she chooses the pool causing the shortest detour.
- If the passenger acts altruistically, he or she chooses the pool with the largest group size and so helps to achieve the largest energy saving.

For both decision rules the pooling potential was calculated. In combination with the criteria of similarity described above, this results in a four-by-four tableau of sixteen scenarios. For each of these scenarios the number of commuters that can be pooled was calculated. The assignment algorithm used is approximate because the order in which the commuters are processed influences the results. However, experimental variations in the order of processing showed no significant changes in the results.

Table 4.1 presents the work trips that can be pooled for the sixteen scenarios. There is a wide range of pooling rates: between 33 and 90 percent. The pooling potential is less if only pooling of total trips is permitted (upper part); but even in the less restrictive scenarios with a maximum accepted walking distance of 1,000 m and a departure time adjustment of 30 minutes three out of four commuters can be pooled. If pooling is permitted for parts of a trip (lower part), even the restrictive scenarios have pooling rates of about 85 percent. The decision criterion 'minimum detour' versus 'maximum passengers' does not affect the total number of pooled work trips but has an impact on the size of the pools. An additional percentage of work trips cannot be pooled because the work trip length is below the maximum walking distance. These commuters are expected to walk. This accounts for 2.4 percent of all commuters for a maximum walking distance of 500 m and 7.7 percent for 1,000 m.

Table 4.1 Total pooling potential of work trips by scenario

	Maximum walking distance	500 m		1000 m	
	Maximum departure time adjustment	15 min	30 min	15 min	30 min
Total trips only	Minimum detour	71 151 *33.4*	91 773 *43.1*	137 889 *64.8*	154 767 *72.7*
	Maximum passengers	70 531 *33.1*	90 848 *42.1*	136 602 *64.1*	153 400 *72.0*
Also parts of trips	Minimum detour	182 188 *85.6*	191 691 *90.0*	190 224 *89.3*	193 043 *90.7*
	Maximum passengers	178 345 *83.8*	188 106 *88.3*	188 560 *88.5*	191 828 *90.1*

Numbers in italics: percent of all work trips

The analysis shows that traffic and so energy consumption of commuter traffic could be substantially reduced by pooling of work trips. There is a large diversity of energy savings between the sixteen scenarios. Four of the restrictive scenarios will even lead to an increase in energy consumption. The explanation for this is that in these scenarios commuters which today use public transport are considered to join a car pool or even use a car as single drivers; this means that they increase their energy consumption. All other scenarios will lead to energy savings between 20 and 55 percent. These reductions are mainly achieved by large savings of car kilometres. Figure 4.9 shows the spatial distribution of saved work trips by car for one of the most restrictive scenarios, i.e. the potential reduction of car traffic if car users join a pool. Like the actual commuting pattern, the potential reduction of traffic is unequally distributed in the urban region. The CBD and the inner city benefit most. There will also be a clear reduction of traffic in the main corridors to the CBD.

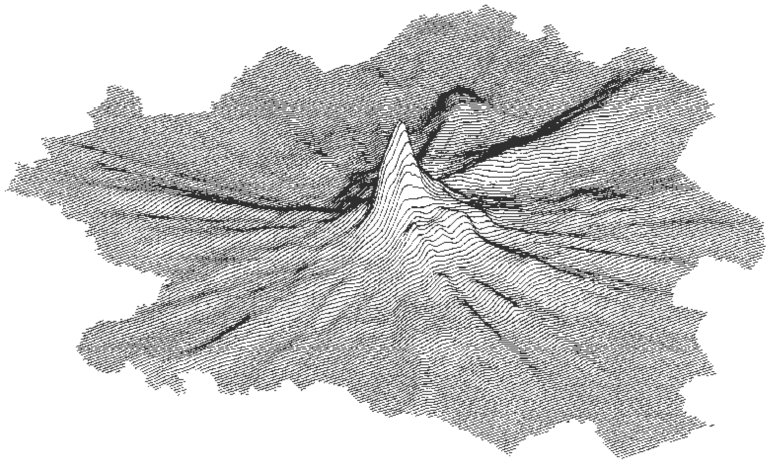


Figure 4.9 Reductions in car traffic of a restrictive scenario.

4.4.2 Accessibility surfaces for Europe

The Treaty on the European Union signed at Maastricht and the White Paper on Growth, Competitiveness and Employment of the European Union both claim that the development of Trans-European Networks (TENs) is an essential element in both promoting the economic development and improving the economic and social cohesion of the Union. It is an important question whether the expectation is right that linking peripheral regions to the European core will stimulate their economic development or whether the implementation of the trans-European transport networks is likely to contribute to spatial polarisation. A full answer to this question would require a comprehensive forecasting model of all flows of goods, persons and services across these networks and how they would change in response to the new transport opportunities, as well as of the economic impacts this would have on the regions. Such a model based on the multiregional input-output framework discussed earlier has been applied to study the regional impacts of the Channel Tunnel and related parts of the European transport network (ACT *et al*., 1996; Fayman *et al*., 1995) but is not applied here. Here it is only asked in which direction the trans-European networks will change the *relative* locational advantage of different parts of the European continent. If the trans-European networks indeed, as the European documents suggest, improve the accessibility of peripheral regions relative to the regions in the European core, it is possible that the peripheral regions benefit economically, though also the opposite may occur. If, however, the trans-European networks increase the difference in accessibility between the central and peripheral regions, they will contribute to spatial polarisation.

Previous accessibility studies have concentrated on accessibility indicators calculated for cities or regions and so have ignored the fact that accessibility is continuous in space and that there are large intraregional differences in accessibility. To represent a continuous surface a raster-based data structure was applied. As no raster-based population data for Europe are available, synthetic raster data were generated using microsimulation in combination with a GIS. For this purpose the European territory was disaggregated into some 70,000 raster cells of 10 km width. The method developed (Spiekermann and Wegener, 1996) follows the suggestion by Newman and Vickerman (1993) that accessibility models should be more disaggregate in spatial resolution.

Two sets of input data were prepared, the distribution of population in Europe and current and future rail travel times in Europe:

- Raster-based population data were generated by the allocation of urban and national population to 10-km raster cells. For each country first the population of large cities was allocated to cells at and close to their geographical location. The number of cells for each city was determined as a function of the total population of the city. After distributing the population of large cities, the remaining population of each country was distributed equally across the rest of the country, i.e. a homogenous density of the rural population was assumed. The result was a data file with estimated population for each of the about 70,000 raster cells of Europe.
- For rail travel times a simplified network was used with travel times of 1993 and estimated travel times for 2010, i.e. travel times with the high-speed rail network of the rail masterplan in operation. The access time from each cell to the nearest node of the network was calculated assuming an air-line travel speed of 30 km/h. The total travel time between two cells therefore consists of three parts: the access time from the origin cell to the nearest network node, the travel time on the network and the terminal time to the destination cell from the node nearest to it. If the direct air-line travel time between two cells is shorter than travel over the network, the shorter direct travel time was used.

Accessibility values were calculated for each of the 70,000 raster cells taking account of the population at and travel time to all other 70,000 raster cells for the years 1993 and 2010. Accessibility was calculated as population potential for which a gravity model was applied

$$A_i = \sum_j \frac{P_j}{c_{ij}^{\alpha}}$$

with P_j representing population in destination cell j and c_{ij} travel time between origin cell i and destination cells j.

The accessibility surfaces so generated are presented in three-dimensional form. Figure 4.10 (top) displays the accessibility surface of the rail network of Europe in 1993. The elevation of the surface at each point indicates the magnitude of the population potential at that point. Strong disparities in accessibility become visible. Urban regions have the highest and rural areas the lowest accessibility. Accessibility decreases from the city centres to the rural areas. Moreover, the areas in central Europe, both urban and rural, have a higher population potential than regions at the European periphery. With a little imagination the 'Blue Banana', the European megalopolis stretching from London along the Rhine corridor to Northern Italy, can be recognised. Figure 4.10 (bottom) contains the accessibility surface of 2010 drawn to the same vertical scale. The only change in input is the assumption that the trans-European high-speed rail network will be in operation by 2010; the assumed distribution of population is the same as for 1993. Because of the significant travel time reductions on the major European rail links the population potential increases all over Europe. However, it appears as if the general accessibility pattern is not much different. The highest accessibility is still found in the major centres of central Europe, whereas the accessibility of the periphery is less than in the centre.

In order to get a closer look at the changes in accessibility induced by the trans-European rail network, Figure 4.11 displays the *change* in accessibility between 1993 and 2020. Figure 4.11 (top) shows absolute change. Now it is clear that, while the general pattern of accessibility has remained the same, the difference between centre and periphery has become more pronounced. The highest absolute changes are in the nodes of the future high-speed rail network, and this growth is much more pronounced in central Europe than in the European periphery.

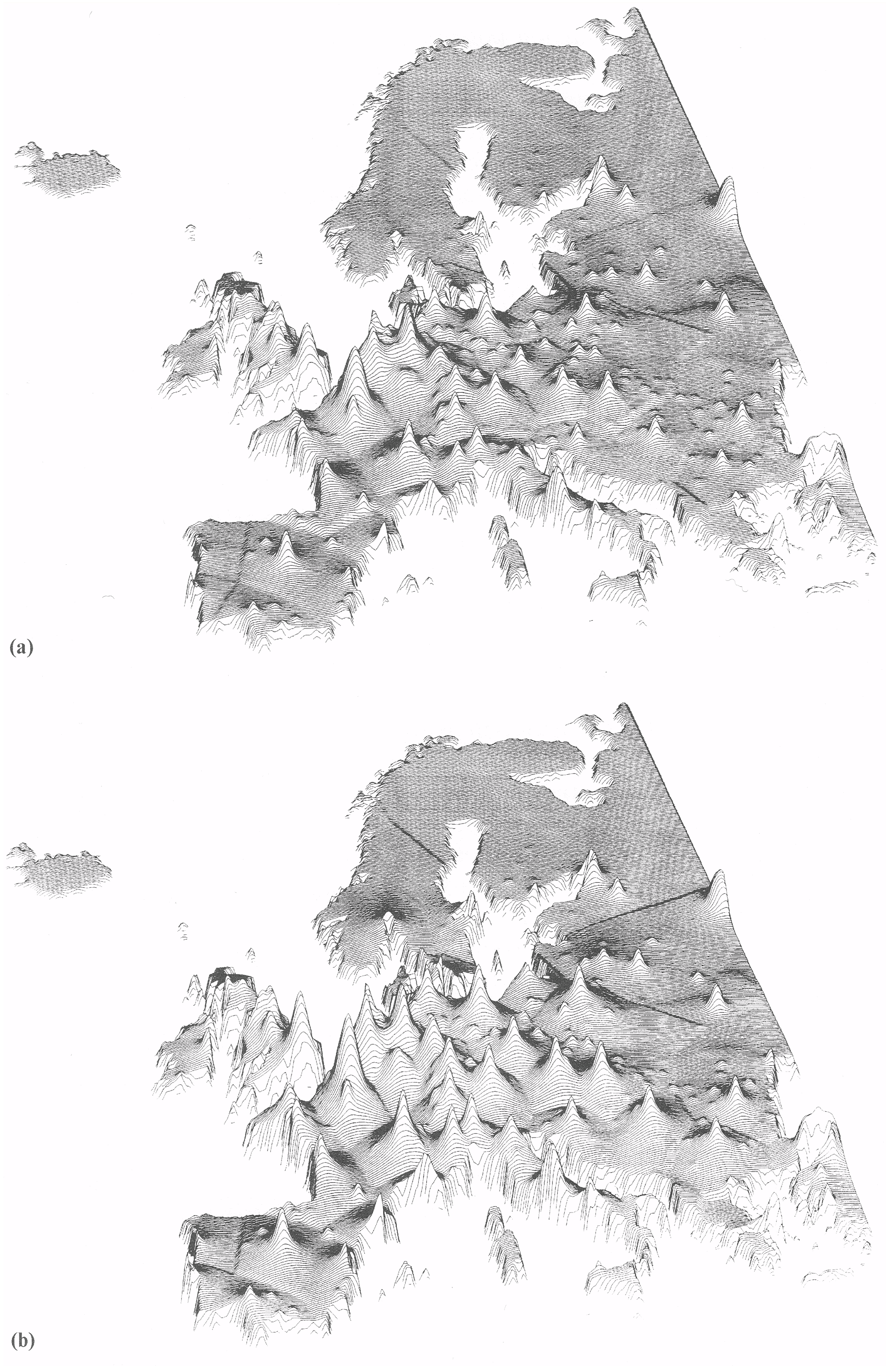
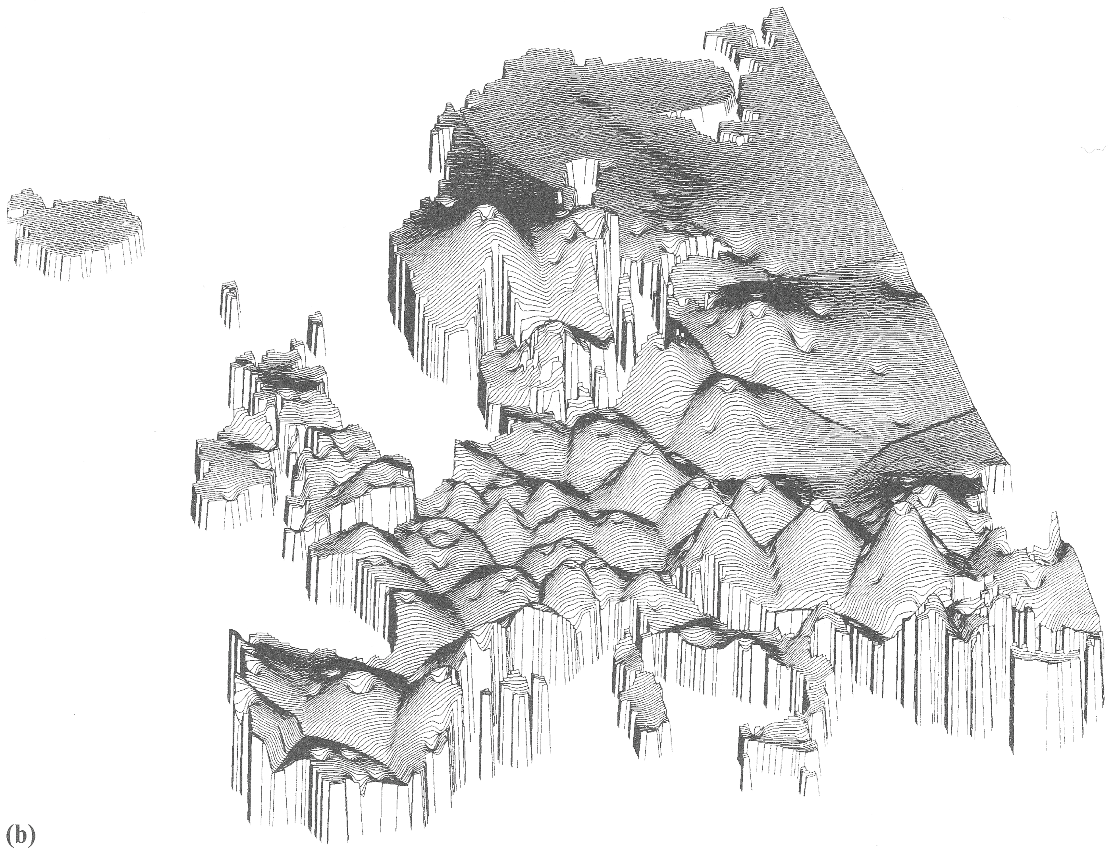


Figure 4.10 Accessibility surfaces of Europe. Accessibility by rail: (a) 1993, (b) 2010.

(a)



(b)

Figure 4.11 Accessibility surfaces of Europe. Accessibility by rail: (a) absolute and (b) relative difference between 1993 and 2010.

This result indicates that the trans-European networks will increase the existing disparities in population potential in Europe in absolute terms. But how about in relative terms? It might be argued that, although the periphery will lose in absolute terms, high relative gains from a low starting position may be more important for economic take-off. Figure 4.11 (bottom) displays change in relative terms, i.e. as a percentage of initial accessibility. Now the picture is different. Peripheral centres such as Oslo, Madrid or Lisbon gain slightly more than centres in the European core such as Paris, which already had a high accessibility. The relative gains are even smaller in the city centres, which appear as craters in the accessibility surface because of their high initial values in 1993. Indeed all peripheral regions, urban or rural, become significantly more accessible by the trans-European networks, if only in relative terms because of their low initial values. However, even in relative terms they gain less than cities which are nodes of the network.

In terms of methodology the analysis presented leaves room for a number of improvements. In particular the population data used in the study need to be more homogenous across countries and regions either by taking data for NUTS 3 regions (which may cause problems of finding appropriate data for eastern Europe) or by using data for NUTS 2 regions and comparable regions in eastern Europe plus data for all European cities with a population of more than 50,000. Also the network data used might be represented with more detail with respect to national and regional networks and all stops in the future high-speed rail network.

CONCLUSIONS

The main argument of the chapter was that the integration of GIS and spatial models might overcome one of the major disadvantages of current spatial models, their low spatial resolution represented by a zonal system. It was demonstrated that GIS can free spatial models from the 'tyranny of zones' and that this opens up a large potential for powerful new models (see Wegener, this volume, Chapter 1). The chapter showed two ways by which GIS may contribute to the development of new models:

- GIS-based data manipulation can be used to create probabilistic micro data sets. A spatial interpolation method for the disaggregation of aggregate data was proposed. The abandonment of the concept of zones altogether and their replacement by a raster-based data organisation is the ultimate solution to the 'modifiable areal unit problem' (Openshaw, 1984; Fotheringham and Wong, 1991; see also Fotheringham, this volume, Chapter 2) and problems of spatial interpolation between incompatible zone systems (Goodchild *et al*., 1993; Fisher and Langford, 1995).
- The data organisation provided by GIS, i.e. vector and raster representations, may be used as common framework for co-processing polygon-, network- and list-based spatial models. In particular the combination of raster and vector representations of spatial elements facilitates activity-based microsimulation of location and mobility in an integrated and consistent way.

The chapter presented two explorative examples for the combination of spatial microsimulation models and GIS. Pooling potential and accessibility are issues that can only be addressed by spatially disaggregate models. The introduction of GIS into spatial modelling widens the range of issues that the models can deal with. In an ongoing research project GIS-based microsimulation is being applied to model hypothetical urban structures subject to new demographic developments, new lifestyles and new transport and information technologies and to systematically evaluate them using criteria such as accessibility, total passenger-km, energy use, land requirement, other environmental indicators and indicators describing the impacts for different social groups, with respect to the three objectives of equity, sustainability and efficiency (Wegener and Spiekermann, 1996b).

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