The Journal of Transport and Land Use http://jtlu.org
Vol. 11 No. 1 [2018] pp. 67–81

# Multi-level urban models: Integration across space, time and policies

**Klaus Spiekermann**
Spiekermann & Wegener Urban and Regional Research, Dortmund
ks@spiekermann-wegener.de

**Michael Wegener**
Spiekermann & Wegener Urban and Regional Research, Dortmund
mw@spiekermann-wegener.de

**Abstract:** Urban and regional models have been developed for different policy fields at different levels of spatial and temporal resolution. But it has become apparent that policies interact across space and time and need to be modelled together. The first urban and regional models were aggregate in space and comparative-static in time. More recently, new data sources and computing techniques have stimulated ever more disaggregation in space and time culminating in agent-based, activity-based microsimulation despite its significant even larger data needs, computing requirements and theoretical problems. This paper argues for models that are instead multi-level and multi-scale in space, time and subsystems. This paper starts with a brief history of urban models and the experience of the authors with the highly integrated urban microsimulation model ILUMASS. Based on this experience, it discusses the benefits and pitfalls of microsimulation and proposes a three-level model system of spatial development, ranging from the European to the local level. The paper closes with new challenges for urban models posed by climate change, energy scarcity, new social problems and new technologies and argues that they make multi-level, multi-scale models even more important and illustrates this by ongoing work with the multi-level model for cities in the Ruhr.

**Keywords:** Urban models, spatial and temporal resolution, equilibrium vs. dynamics

**Article history:**
Received: March 30, 2017
Accepted: August 4, 2017
Available online: January 5, 2018

## 1 Introduction

The first efforts to understand the spatial development of cities were physical: the ring model (Burgess, 1925), the sector model (Hoyt, 1939) and the polycentric model (Harris & Ullman, 1945). Only in the 1950s it became generally recognized that ease of access was one of the significant drivers of land use development. Hansen (1959) demonstrated for Washington, DC that locations with good accessibility had a higher chance of being developed, and at a higher density, than remote locations ("How accessibility shapes land use"). The recognition that therefore transport and land use planning need

---

http://dx.doi.org/10.5198/jtlu.2018.1185
ISSN: 1938-7849

The *Journal of Transport and Land Use* is the official journal of the World Society for Transport and Land Use (WSTLUR) and is published and sponsored by the University of Minnesota Center for Transportation Studies.

to be coordinated, led to first attempts to capture the relationship between transport and land use in mathematical models.

The first land-use transport models were engineering models. Their aim was to improve the forecasts of origins and destinations that drove the transport models with the aim to overcome road congestion. This engineering bias was one of the reasons why the models were heavily challenged in the 1970s by critics such as Lee (1973). Only in the 1980s the models responded to this challenge by becoming more diversified in terms of age and income, trip purposes and travel modes to deliver indicators, such as social and spatial equity and access to services of general interest. And even more recently also environmental indicators, such as air quality and traffic noise have been added to the repertoire of model output indicators of the most advanced urban models, a pioneering example was the UrbanSim model (Waddell, 2002). This broadening of scope forced modelers to consider and quantify not only the interaction between land use and transport but also the influences of economic, social and environmental factors.

In parallel with this broadening of scope, urban models became more and more expected to provide more long-term forecasts. This was due to the growing awareness that urban change processes differ in speed and duration and that therefore urban policies need to adopt a long-range perspective. And thirdly it became obvious that significant interactions exist between spatial levels: that the spatial development of cities depends on the economic and social development of neighboring or even far-away regions and the interactions between them, such as trade and migration flows.

How the modelling community has dealt with this broadening of scope, time and space of urban problems is the theme of this paper. The paper argues for models that are multi-level and multi-scale in space, time and subsystems. It starts with a brief history of urban models and the experience of the authors with the highly integrated urban microsimulation model ILUMASS. Based on this experience it discusses the benefits and pitfalls of microsimulation and proposes a three-level model system of spatial development ranging from the European to the local level, in which each level is organized at the most appropriate resolution. The paper closes with new challenges for urban models posed by climate change, energy scarcity, new social problems and new technologies and argues that they make multi-level, multi-scale models even more important, and illustrates this by ongoing work with the multi-level model for cities in the Ruhr.

## 2 Trends in urban modelling

There is a long tradition of modelling individual dimensions of urban development. The first urban models were transport models, in which the impacts of transport investments on trip generation, trip distribution, modal split and traffic congestion were predicted. The transport models were complemented by land use models, in which the two-way interactions between transport and location choice were modelled. In more recent times models have responded to the growing attention for the environmental by addressing environmental aspects such as energy consumption, greenhouse gas emissions, air quality and traffic noise. However, there are only few models in which all these aspects are dealt with in one integrated model.

The first urban and regional models were aggregate in space and comparative-static in time. (Wegener, 2014). More recently models have become dynamic, i.e., project the development of cities over time taking account of different speeds of urban change processes and the resulting delays in response to external changes. Even more recently new data sources from satellites and social networks ('big data') and computing techniques (parallel computing) have stimulated ever more disaggregation in space and time culminating in agent-based, activity-based microsimulation.

These developments have divided the urban modelling community in two camps. On the one hand, there are enthusiasts who believe in the potential of new data sources and computing techniques and envisage a world of high-resolution models able to predict the minute-by-minute behavior of individual persons or vehicles. On the other hand, there are sceptics who have become concerned about the unsolved theoretical problems, still unknown risks for privacy and the still immense computing time requirements of microscopic models and therefore argue for other ways to deal with urban complexity. The authors of this paper belong to the second camp and will demonstrate their experience in the following sections.

### 2.1 Microsimulation

New activity-based microsimulation models improve urban simulation modelling: Lifestyles can be represented, i.e., households and individuals can be disaggregated to the agent level. Environmental impacts and feedback can be modelled with the required spatial resolution. Population and employment can be represented by their decision-making units, i.e., households and firms. Microlocations can be represented. Households affected by environmental impacts can be localized.

However, to date, no full-scale microsimulation model of urban land use, transport and environment has become operational. There are still unresolved problems regarding the interfaces between the sub-models. The feedback between environmental quality and location has not yet been implemented. The computing time for existing models is calculated in terms of weeks or days, not hours. Serious problems of calibration, instability and random fluctuations have not yet been solved (Wegener, 2011b).

There are ultimate limits to increasing the substantive, spatial and temporal resolution of behavioral models: There are theoretical limits when the number of processes simulated is too small to yield reliable results. There are empirical limits when the marginal costs of obtaining micro data are larger than their added value. There are practical limits when the computing time of the models exceeds the duration of the modelled processes. There are ethical limits to the collection of data about private lives for purposes of research.

How much micro is enough? There seems to be little consideration of the benefits and costs of microsimulation: Where is microsimulation really needed? What is the price for microsimulation? Would a more aggregate model do?

One of the authors of this paper belongs to the early adopters of microsimulation in urban modelling (Wegener, 1985). Both authors developed methods to disaggregate spatial data (Spiekermann, 2003) and synthetic populations (Moeckel, Spiekermann, & Wegener, 2003) in a large inter-university project to build a comprehensive urban microsimulation model. Their experience with this project will be briefly presented in the following section.

### 2.2 The ILUMASS project

The project ILUMASS (Integrated Land-Use Modelling and Transport Systems Simulation) (Beckmann et al., 2007) combined a microscopic activity-based simulation model of urban traffic flows and a microscopic agent-based model of household and firm development and the resulting changes of land and housing markets and a model of environmental impacts (Figure 1). The model simulated the behavior of 2.6 million persons in 1.2 million households and dwellings, 80,000 firms on 92,000 industrial sites in 300 zones or 209,000 raster cells of 100x100 m size. A typical run over 30 years took 3-5 days of computing time.

The ILUMASS project was quite successful in developing individual sub-models. However, it was not successful in implementing the planned integrated model of land use and transport (Wagner & Wegener, 2007): The land use, transport and environment sub-models of ILUMASS were independent executables. The application programming interface (API) connecting sub-models via files never worked properly. Data exchange between sub-models was slow. The computing times of the transport sub-models were excessive.

After the end of the project a test was undertaken by replacing the microscopic transport and environmental sub-models by an aggregate transport model and by simpler environmental impact models. The resulting "little" ILUMASS model took only 90 minutes for the whole 30-year simulation.

## 3 Multi-level, multi-scale models

The position presented in this paper is that for each planning problem there is an appropriate level of temporal, spatial and conceptual resolution. Because of the interactions between regional, urban and local processes discussed above, this calls for a multi-level, multi-scale system of regional, urban and local models instead of one model covering all spatial levels and scales. There are several urban-regional models that have implemented this principle, such as DELTA (Simmonds, 1999) and PECAS (Hunt & Abraham, 2005).

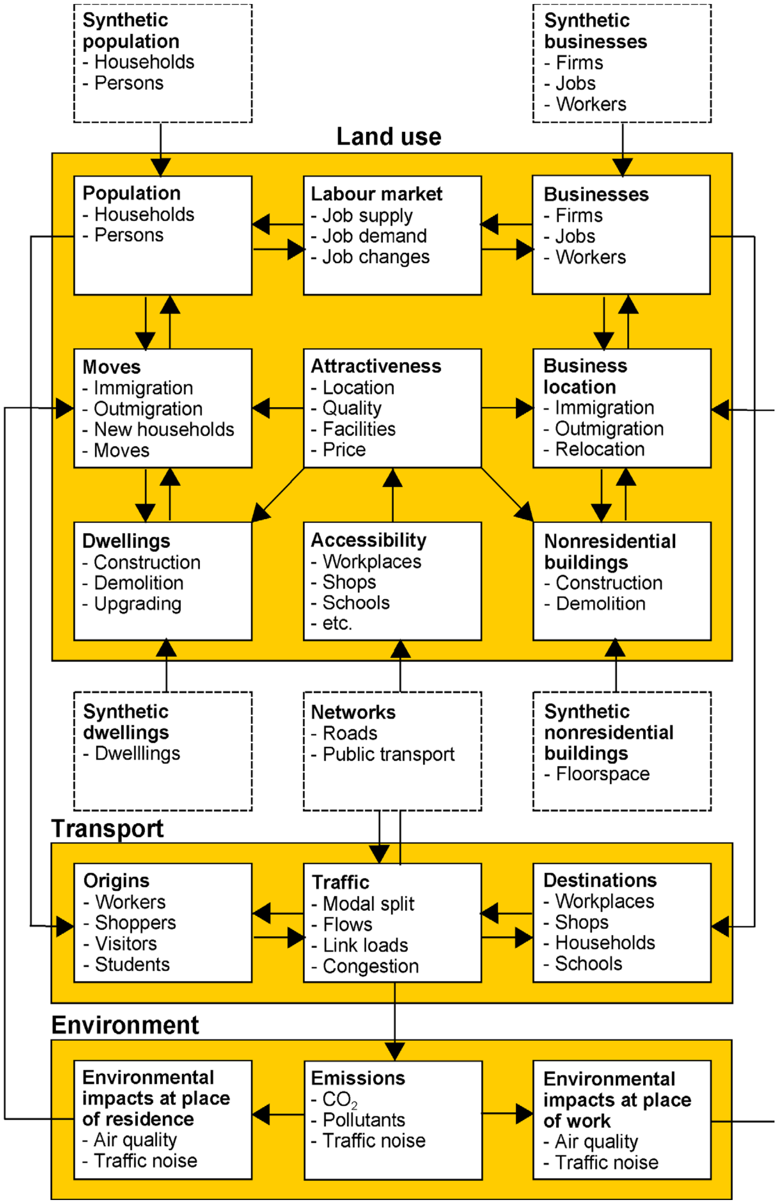

**Figure 1:** The ILUMASS model

In this section, such a three-level model implemented in the EU Fifth Framework project STEPs "Transport Strategies under the Scarcity of Energy Supply" (Fiorello et al., 2006) will be presented.

The aim of the project was to develop, compare and assess possible scenarios for the transport system and energy supply of the future taking into account the autonomy and security of energy supply, effects on the environment, the economy and technological development and the impacts of measures to internalize external costs and the interactions between transport and spatial development. For this it applied and linked three models: the regional economic SASI model (Wegener, 2008), the urban IRPUD model (Wegener, 2011a) and the local environmental Raster model (Spiekermann, 2003). Figure 2 visualizes the three model levels.

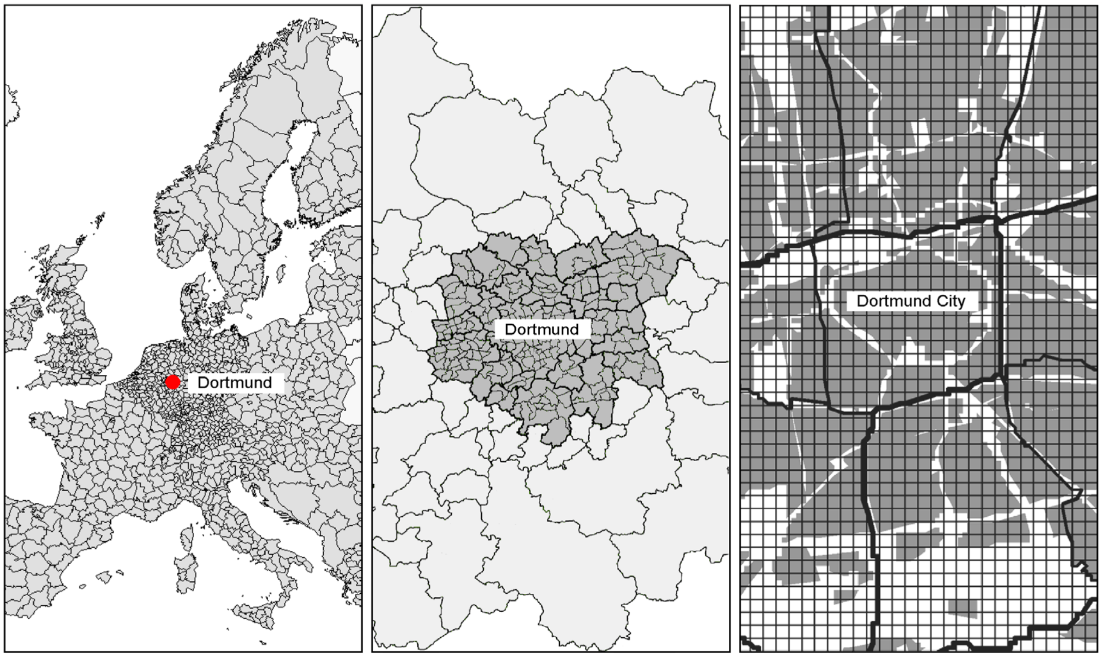

**Figure 2:** The three model levels

### 3.1 Regional level: the SASI model

The SASI model is a recursive-dynamic simulation model of socio-economic development of 1,321 NUTS-3 regions in Europe under exogenous assumptions about the economic and demographic development of the European Union, transport infrastructure investments and other transport policies, in particular the trans-European transport networks (TENT). The SASI model differs from other regional economic models by modelling not only production (the demand side of labor markets) but also population (the supply side of labor markets). Figure 3 shows the sub-models of the SASI model and its interactions.

In the STEPs project the SASI model was used to forecast economic development, population and net migration in the Dortmund urban area, for each year of the forecasting period as framework for the scenarios simulated with the IRPUD model.

### 3.2 Urban level: the IRPUD model

In the STEPs project the IRPUD model was then used to simulate scenarios of fuel price increases and different combinations of do-nothing, business-as-usual, infrastructure and technology and demand regulation policies and a combination of all policies.

The IRPUD model is a dynamic simulation model of intraregional location and mobility decisions in an urban region. It receives its spatial dimension by the subdivision of the study area into 246 internal zones representing statistical districts and 53 external zones representing municipalities connected with each other by transport networks containing the most important links of the public transport and road networks coded as an integrated, multimodal network including all past and future network changes. It receives its temporal dimension by the subdivision of time into periods of one or more years' duration. The model predicts for each simulation period intraregional location decisions of industry, residential developers and households, the resulting migration and travel patterns, construction activity and land use development and the impacts of public policies in the fields of industrial development, housing, public facilities and transport. Figure 4 is a schematic diagram of the major subsystems considered in the model and their interactions.

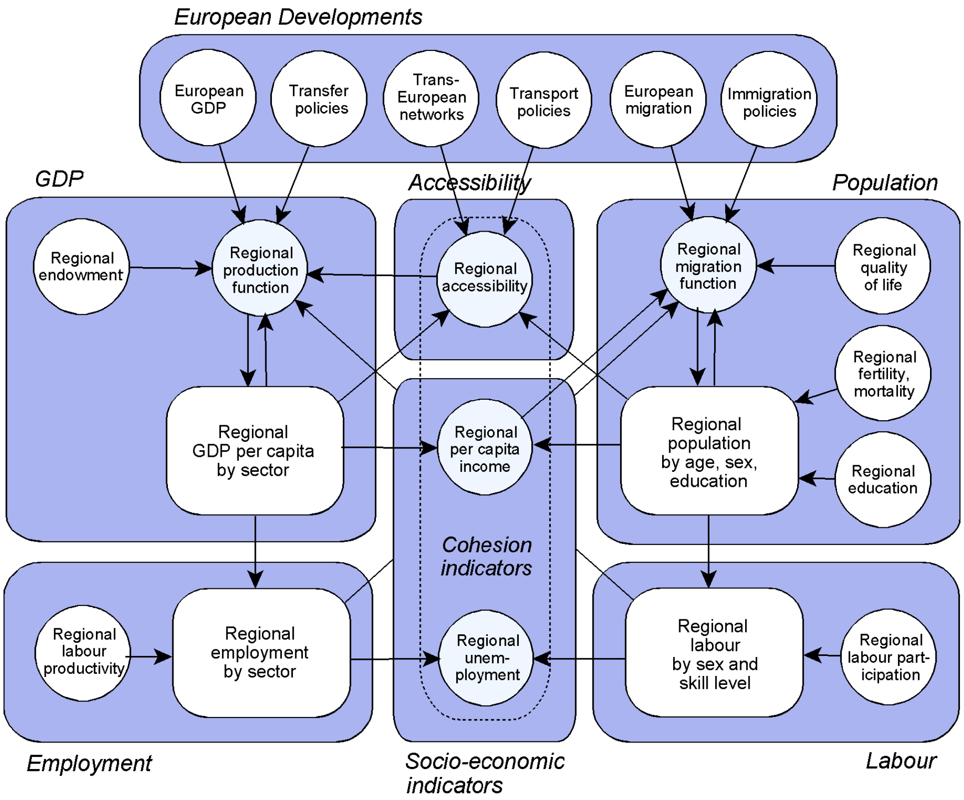

**Figure 3:** The SASI model

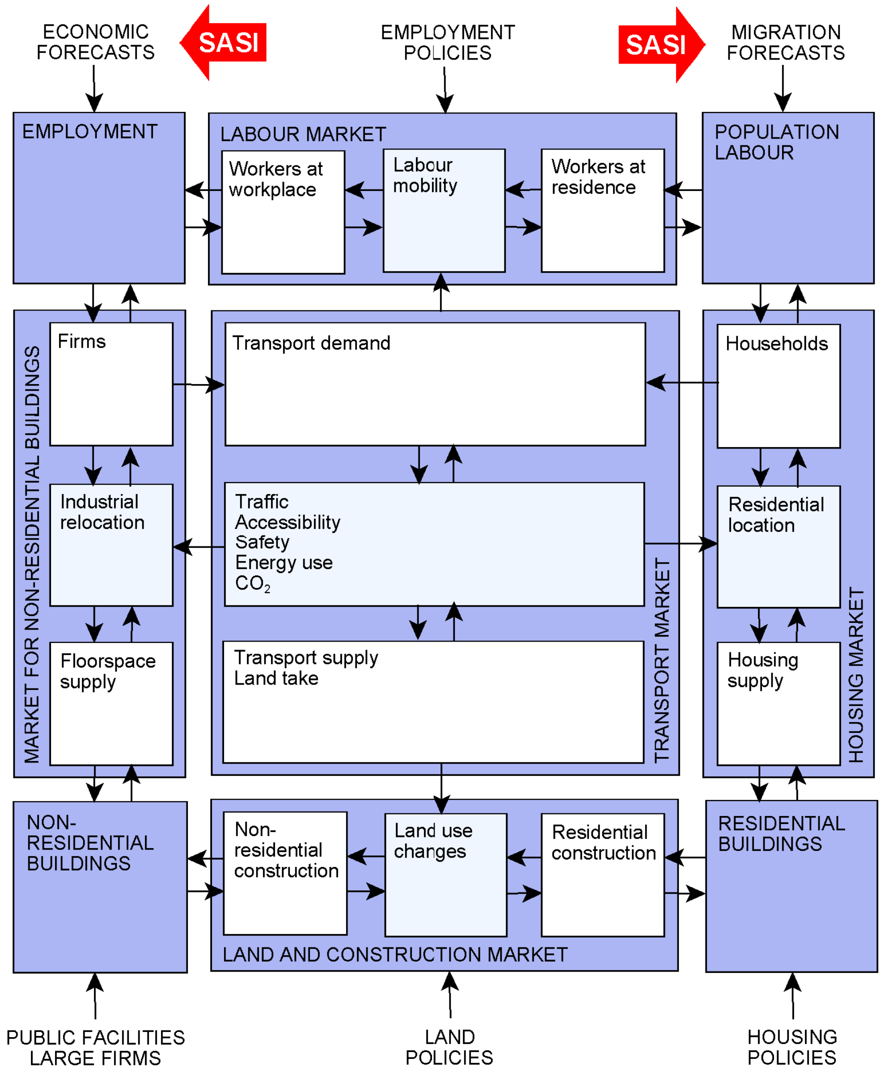

**Figure 4:** The IRPUD model

The four square boxes in the corners of the diagram show the major stock variables of the model: population, employment, residential buildings (housing) and non-residential buildings (industrial and commercial workplaces and public facilities). The actors representing these stocks are individuals or households, workers, housing investors and firms. These actors interact on five submarkets of urban development: the labor market, the market for non-residential buildings, the housing market, the land and construction market and the transport market. For each submarket, the diagram shows supply and demand and the resulting market transactions. The arrows at the outside of the diagram indicate exogenous inputs: they are either forecasts of regional employment and migration by the SASI model subject to long-term economic and demographic trends or policies in the fields of industrial development, housing, public facilities and transport.

With respect to resolution, the IRPUD model is a hybrid between aggregate and disaggregate models as its model of the urban housing market is microscopic, i.e., models the moving behavior of individual households but at a zonal level. In fact, it was one of the earliest microscopic housing market models (Wegener, 1985), anticipating many features of the most advanced current models of this kind (Moeckel, 2017).

### 3.3 Local level: the Raster model

In STEPs the highest resolution was reserved for modelling environmental impacts, greenhouse gas and pollutant emissions, air quality and distribution of traffic noise. This required disaggregation of the results of the land use and transport models to about 200,000 grid cells with a size of 1 ha each, the calculation of impacts for these grid cells and their visualization in diagrams and maps. In order to calculate such indicators, the so-called Raster model had been developed in the EU 5th RTD Framework project PROPOLIS (Spiekermann, 2003; Lautso et al., 2004). Figure 5 contains the main components of the Raster model.

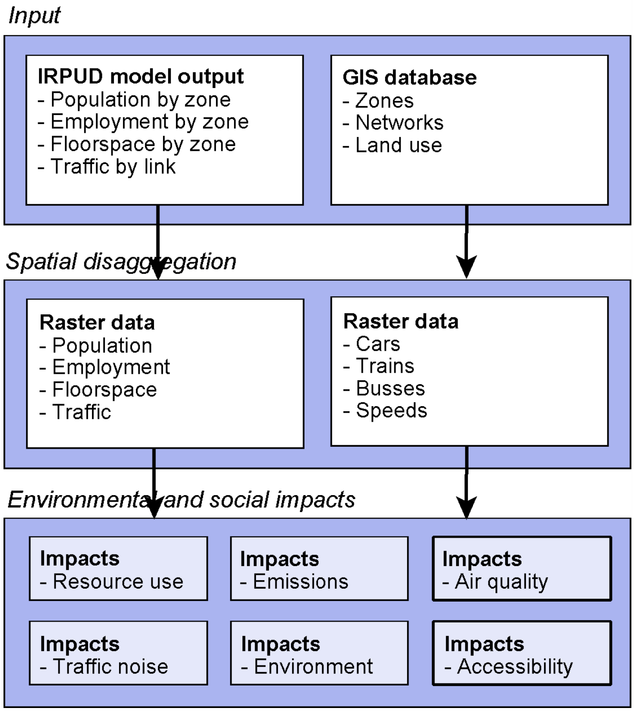

**Figure 5:** The Raster model

The Raster model maintains the zonal and network organization of the land-use transport model and adds a disaggregate raster-based representation of space. There are two main sources of input, (1) a spatial database containing zone boundaries and land use categories as polygons and the network coded as vectors, and (2) the policy-dependent forecasts by the IRPUD model for the location of households by socio-economic group, employment and floor space in the zones and the traffic flows on the links of the network. Raster disaggregation is applied to socio-economic data and network data.

Using this information, environmental and social impact sub-models assess emissions, air quality, noise levels, population exposure, environmental quality and accessibility in each raster cell. The emission sub-model relates the traffic flows with speed-related emission functions and calculates emissions of several air pollutants and greenhouse gases as well as transport energy use. The air pollution sub-model calculates dispersion of pollutants and the exposure of population to it. The noise sub-model models the sequence from noise generation via noise propagation to noise levels and population exposure to noise.

Resource use, quality of open space and accessibility of open space are handled in two more sub-models.

## 4 Results

The three-level model system, when run together, produced coherent results at each level of resolution in maps, difference maps (maps showing the differences between scenarios) and diagrams showing trajectories of variables between the base and target years for individual countries or regions or for comparison between scenarios. Figures 6-8 show examples of the results with different spatial resolution, for lack of space only maps are shown.

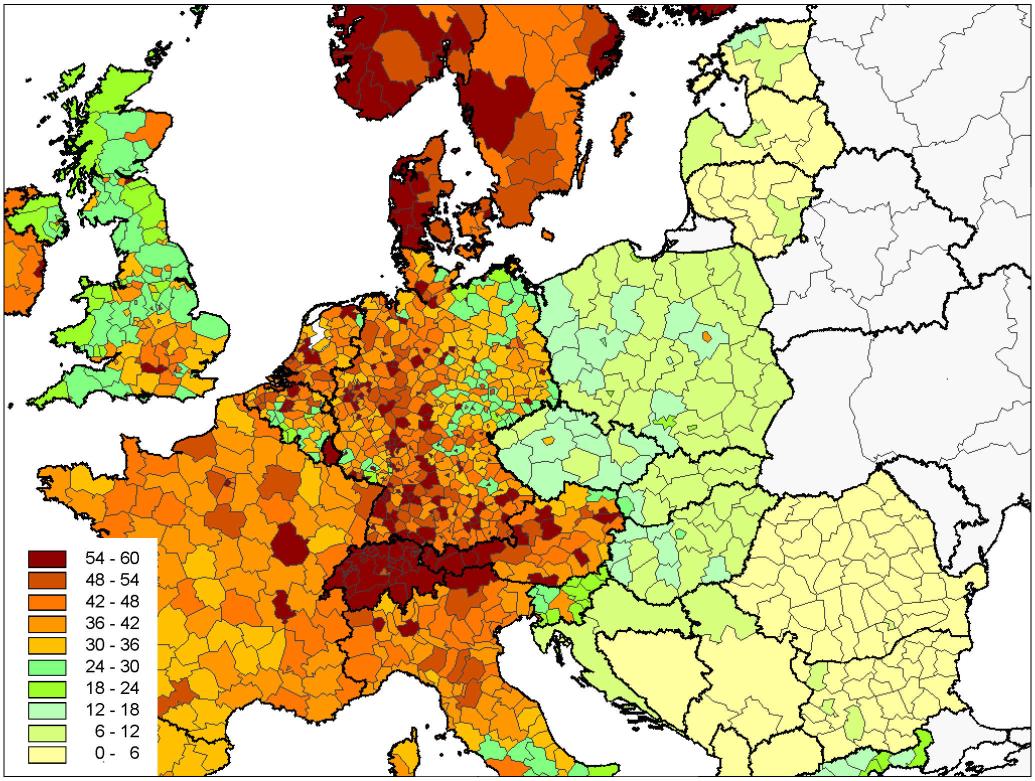

**Figure 6:** SASI model output: GDP per capita 2030 in European regions (1,000 €)

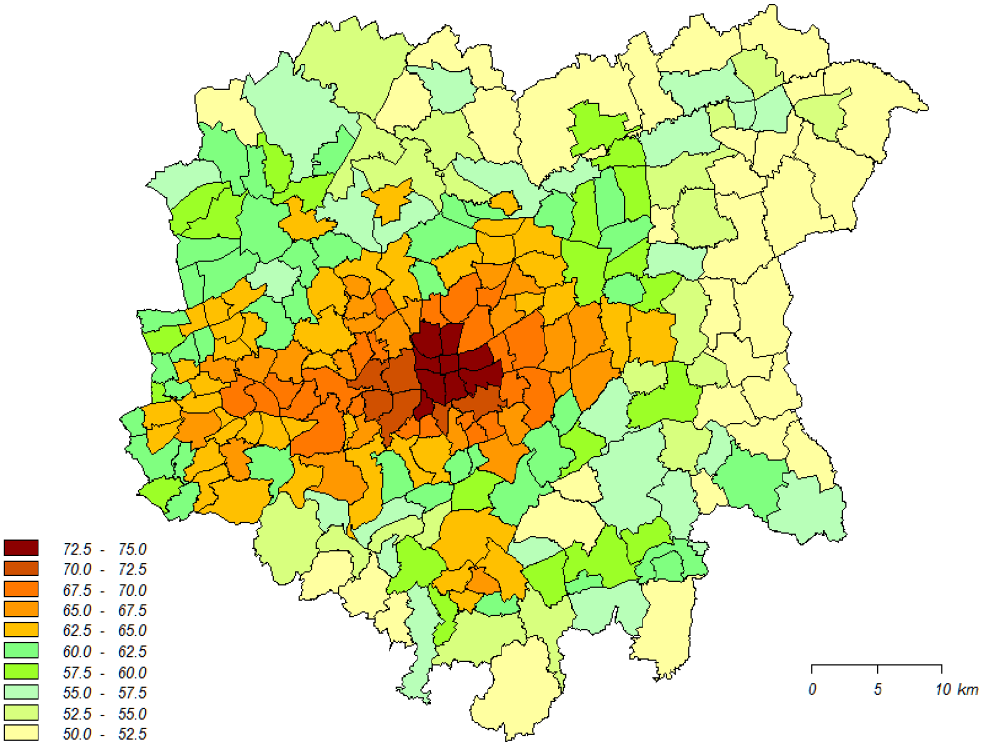

**Figure 7:** IRPUD model output: Accessibility to jobs in the Dortmund region 2030

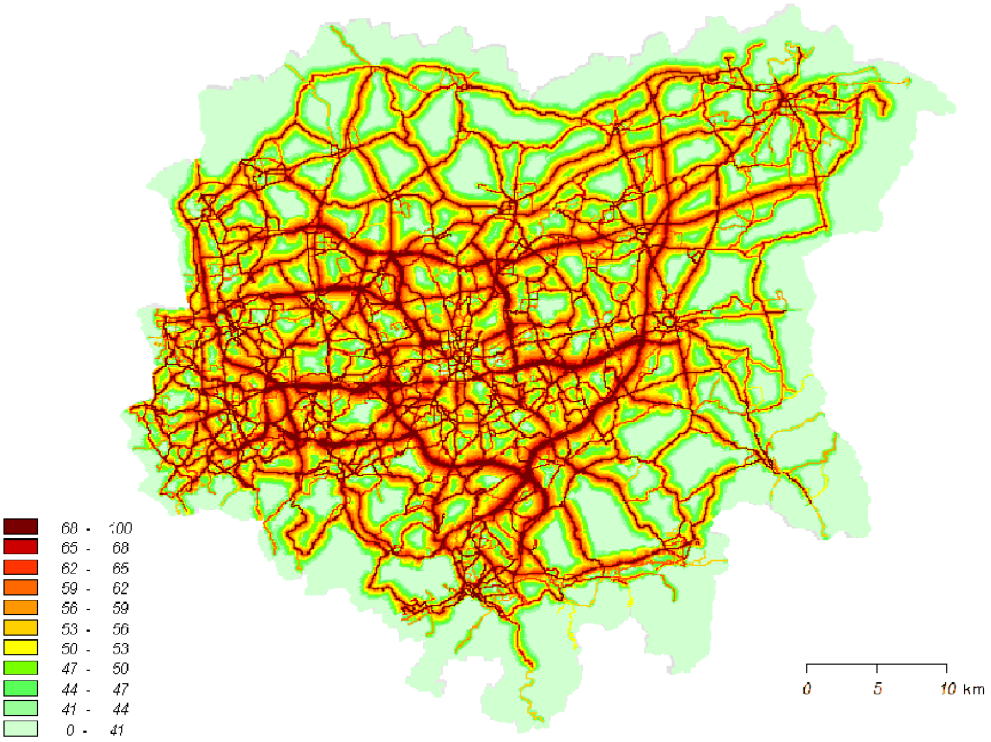

**Figure 8:** Raster model output: Peak hour traffic noise in the Dortmund region 2030 (dB(A))

## 5 New challenges for urban models

The reconsideration of the common trend towards ever more disaggregation and large data volumes and the reasons for multi-level models become even more relevant if ongoing substantial changes in the political context of urban development are considered. To cope with the challenges of energy scarcity, climate change and refugee migration, urban models will need to be able to predict the decision behavior of households and firms under fundamentally different conditions:

- The need to mitigate climate change will require not only new transport technologies, such as more energy-efficient cars or electric vehicles, but it will also require push measures, such as high carbon or fuel taxes, high road pricing or congestion charges, rigorous speed limits and car-free zones. At the same time the necessary heavy use of public transport will exceed the capacity of public transport facilities, something not thought to be possible in the past.
- Even with these measures climate change adaptation measures, such as flood prevention and management and rigorous land use controls to prevent development in floodplains and fresh-air corridors, need to be considered.
- Energy will become scarce and more expensive, and this will require alternative vehicles and/or fuels, decentralized energy production (solar, geothermal, photovoltaic) and better heat insulation of buildings.
- Increasing pressure of refugee immigration from African and Middle East countries caused by poor economic conditions, poverty and climate change (floods, droughts and famine) will create huge yet unknown problems of housing and integration for cities.
- All this will create new forms of social conflict for groups or communities most affected by climate change and energy scarcity and will require minimum standards of access to basic services.

In addition, technological and behavioral trends already now apparent, such as car-sharing, online shopping and self-driving cars will need to be considered. None of these new developments have been dealt with by most current urban models but need to be addressed in the future.

And these new challenges will have impacts on the priorities and standards of urban modelling. Because the changes will be so large, it will be necessary to focus less on detail and more on basic essentials. Moreover, data collected in sunshine days will become of less value for explaining behavior in stormy days after fundamental changes, so extrapolation will become more and more useless. For the same reason equilibrium in urban markets will become the exception, so urban dynamics and shocks will need to be addressed. This implies that behavior observed in the past will be less relevant and attention should be paid to anthropological needs that remain stable even after big changes. For the same reason preferences will become less important than constraints that limit choices for underprivileged groups of society.

All this will have significant impacts on the methods of urban modelling. Statistical calibration of model equations will become less important and validation through expert judgment and plausibility analysis more important. Finally, the most frequent questions to be answered by urban modelling will change. Whereas in the past urban models were mainly expected to answer what-if questions, i.e., to forecast what would occur if certain assumptions about trends and policies would come true, in the future the emphasis could likely move toward backcasting (don't ask what can be done but what needs to be done).

## 6 Ongoing work: The Ruhr model

As an example of response to some of these challenges in this section ongoing work with the SASI and IRPUD models will be briefly described. In the project "Implementing the Energy Transition in the Communities of the Ruhr Area" (WI, 2017) the IRPUD model was extended in three dimensions to the Ruhr model: by extending its study area to the whole Ruhr region (population 5.3 million), by extending its forecasting horizon until 2050 and by extending it by new sub-models of residential building energy, electro mobility, car-sharing and cycling (Fuerst & Wegener, 2017; Huber, Schwarze, Spiekermann, & Wegener, 2013; Brosch, Huber, Schwarze, Spiekermann, & Wegener; 2016; Schwarze et al., 2017).

Figure 9 summarizes the results of the Ruhr model. In total 20 different scenarios were simulated examining the likely impacts of assumptions of the SASI model about economic development and immigration and different planning measures from the policy fields land use planning, energy efficiency and transport. The transport measures tested included push measures aimed at making car traffic less attractive and pull measures aimed at making public transport, cycling and walking more attractive. In addition, six integrated strategies were analyzed consisting of different combinations of individual policy measures in order to identify possible positive or negative synergies between them. Moreover, all scenarios were simulated with two different assumptions about fuel energy price development: In the A scenarios it was assumed that fuel prices would rise by only one percent per annum, whereas in the B scenarios it was assumed that fuel prices would increase by four percent per annum.

The horizontal bars in Figure 9 visualize the changes in $CO_2$ emissions of the scenarios simulated compared with the business-as-usual base scenario with low fuel prices. The results can be summarized as follows:

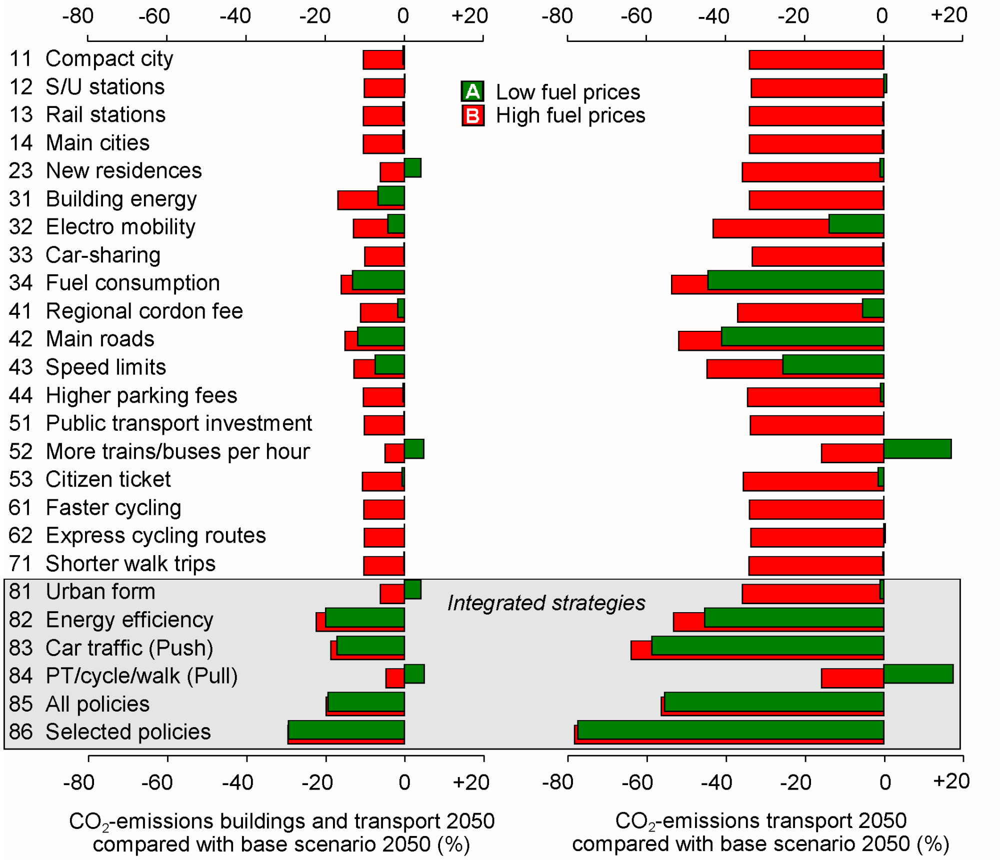

**Figure 9:** Results of the Ruhr model

- The effects of the scenarios on the $CO_2$ emissions of buildings and transport seen together are reductions of up to 30 percent, however, considering only the $CO_2$ emissions of transport, the scenarios are much more effective with possible decreases of up to 80 percent.
- Push scenarios making car driving less attractive are more effective than pull scenarios making public transport, cycling and walking more attractive.
- Integrated strategies combining policies from different policy fields are more effective than individual policies.

In the future, besides the existing sub-models of energy consumption of residential buildings and person travel, other energy-related sub-models are planned: energy consumption of non-residential buildings, industrial and commercial processes, household appliances, and local goods transport, as well as generation of solar and wind energy.

In addition, it is planned to integrate the model with the high-resolution Raster model of environmental impacts of land use and transport so that it predicts not only environmental impacts but also their effects on the location decisions of households and firms (Spiekermann & Wegener, 2008). The environmental impact sub-models (air quality, traffic noise, biodiversity) are already available but will have to be dynamically linked to the integrated model to make that feedback possible.

## 7 Conclusions

This paper critically assessed the common trend in urban modelling towards ever more spatial and substantive resolution. Based on their experience with the development and implementation of a universal microscopic urban model the authors propose and demonstrate multi-level and multiscale urban models as a more appropriate way towards integration across space, time and policy fields. They support their view by likely future changes in the political context of urban development.

In conclusion it can be assumed that urban development will in the future be much more determined by fundamental change (Wegener, 2013): The fundamental changes in the problems and priorities of urban planning will have deep impacts on the philosophy and method of urban modelling: It will be necessary to concentrate less on detail and more on basic essentials, to rely less on extrapolation and more on fundamental change, less on equilibrium and more on dynamics, less on observed behavior and more on theories of need, and to put less emphasis on modelling preferences but more on constraints. In technical terms calibration will become less important and plausibility analysis more important, and forecasting will become less relevant, while backcasting (don't ask what can be done but what needs to be done) will become more important.

These considerations lead to a reassessment of the hypothesis that in the future all spatial modelling will be microscopic and agent-based. Under constraints of data collection and computing time, there is for each planning problem an optimum level of conceptual, spatial and temporal resolution. This suggests working toward a theory of balanced multi-level models which are as complex as necessary for the planning task at hand and — to quote Albert Einstein — "as simple as possible but no simpler."

## References

Beckmann, K. J., Brüggemann, U., Gräfe, J., Huber, F., Meiners, H., Mieth, P., Moeckel, R., Mühlhans, H., Schaub, H., Schrader, R., Schürmann, C., Schwarze, B., Spiekermann, K., Strauch, D., Spahn, M., Wagner, P., & Wegener, M. (2007). *ILUMASS: Integrated land-use modelling and transport system simulation.* Final Report. Berlin: Deutsches Zentrum für Luft und Raumfahrt. Retrieved from http://www.spiekermann-wegener.de/pro/pdf/ILUMASS_Endbericht.pdf

Brosch, K., Huber, F., Schwarze, B., Spiekermann, K., & Wegener, M. (2016). Integrierte Stadtmodellierung: Flächennutzung, Verkehr, Energie, Umwelt. In H. Schmitt, R. Danielzyk, S. Greiving, D. Gruehn, N. X. Thinh, & B. Warner (Eds.), *Raummuster – Struktur – Dynamik – Planung.* Dortmunder Reihe zur Raumplanung 147 (pp. 229–241). Essen: Klartext Verlag.

Burgess, E. W. (1925). The growth of the city. In E. W. Burgess & R. W. McKenzie (Eds.), *The city*, pp 47–62. Chicago: Chicago University Press.

Fiorello, D., Huismans, G., López, E., Marques, C., Steenberghen, T., Wegener, M., & Zografos, G. (2006). *Transport strategies under the scarcity of energy supply.* STEPs Final Report. A. Monzon & A. Nuijten (Eds). Den Haag: Buck Consultants International. Retrieved from http://www.spiekermann-wegener.de/pro/pdf/STEPs_Final_Report.pdf

Fuerst, F. & Wegener, M. (2017). Energy efficiency of buildings: A challenge for urban models. In Jin, Y. (Ed.), *Applied urban modelling: Assessing pathways toward energy efficient and climate-wise regions.* Cambridge: British Academy.

Hansen W. G. (1959). How accessibility shapes land use. *Journal of the American Institute of Planners, 25*(2), 73–76.

Harris, C. D., & Ullman, E. L. (1945). The nature of cities. *Annals of the American Academy of Political and Social Sciences, 242,* 7–17.

Hoyt, H. (1939). *Structure and growth of residential neighborhoods in American cities.* Washington, DC: Federal Housing Administration.

Huber, F., Schwarze, B., Spiekermann, K., & Wegener, M. (2013). Modelling the energy transition in cities. Paper presented at the 13th International Conference on Computers in Urban Planning and Urban Management, Utrecht, July 2–4, 2013. Retrieved from http://www.spiekermann-wegener.de/pro/pdf/EWR_1.1.1_HSSW_CUPUM2013.pdf

Hunt, J. D., & Abraham, J. E. (2005). Design and implementation of PECAS: A generalized system for the allocation of economic production and consumption quantities. In M. E. H. Lee-Gosselin & S.T. Doherty (Eds.). *Integrated land-use and transportation models: Behavioral foundations* (pp 253–274). St. Louis, MO: Elsevier.

Lautso, K., Spiekermann, K., Wegener, M., Sheppard, I., Steadman, P., Martino, A., Domingo, R., & Gayda, S. (2004). *PROPOLIS: Planning and research of policies for land use and transport for increasing urban sustainability*. PROPOLIS Final Report. Helsinki: LT Consultants. Retrieved from http://www.spiekermann-wegener.de/pro/pdf/PROPOLIS_Final_Report.pdf

Lee, D. B. (1973). Requiem for large-scale models. *Journal of the American Institute of Planners, 39*(3), 163–178.

Moeckel, R. (2017). Constraints in household relocation: Modeling land-use/transport interactions that respect time and monetary budgets. *Journal of Transport and Land Use, 10*(2), 1–18. Retrieved from https://www.jtlu.org/index.php/jtlu/article/download/810/863

Moeckel, R., Spiekermann, K., & Wegener, M. (2003). Creating a synthetic population. *Proceedings of the 8th International Conference on Computers in Urban Planning and Urban Management* (CUPUM). Sendai, Japan: Center for Northeast Asian Studies. Retrieved from http://www.spiekermann-wegener.de/pub/pdf/CUPUM_2003_Synpop.pdf

Schwarze, B., Spiekermann, K., Wegener, M., Huber, F., Brosch, K., Reutter, O., & Müller, M. (2017). *Cities and climate change: Ruhr area 2050. Integrated Ruhr area model and regional modal shift.* Dortmund/Wuppertal, Germany: Spiekermann & Wegener Urban and Regional Research, University of Wuppertal, Wuppertal Institute for Environment, Climate and Energy. Retrieved from http://www.spiekermann-wegener.de/pro/pdf/EWR_Ruhr_Area_260717.pdf

Simmonds, D. (1999). The design of the DELTA land-use modelling package. *Environment and Planning B, 26,* 665–684.

Spiekermann, K. (2003). *The PROPOLIS Raster module.* Deliverable D4 of PROPOLIS. Dortmund, Germany: Spiekermann & Wegener Urban and Regional Research. Retrieved from http://www.spiekermann-wegener.de/pro/pdf/PROPOLIS_D4.pdf

Spiekermann, K., & Wegener, M. (2008). Environmental feedback in urban models. *International Journal of Sustainable Transport, 2*, 41–57.

Waddell, P. (2002). UrbanSim: Modeling urban development for land use, transportation and environmental planning. *Journal of the American Planning Association, 68*, 297–314.

Wagner, P., & Wegener, M. (2007). Urban land use, transport and environment models: Experiences with an integrated microscopic approach. *disP, 170*(3), 45–56. Retrieved from http://www.spiekermann-wegener.de/pub/pdf/PWMW_ILUMASS.pdf

Wegener, M. (1985). The Dortmund housing market model: A Monte Carlo simulation of a regional housing market. In K. Stahl (Ed.), *Microeconomic models of housing markets,* pp. 144–191. Berlin/Heidelberg/New York: Springer Verlag. Retrieved from http://www.spiekermann-wegener.de/pub/pdf/MW_Housing_Market_1985.pdf

Wegener, M. (2008). *SASI model description.* Working Paper 08/01. Dortmund, Germany: Spiekermann & Wegener Urban and Regional Research. Retrieved from http://www.spiekermann-wegener.de/mod/pdf/AP_0801.pdf

Wegener, M. (2011a). *The IRPUD model.* Working Paper 11/01. Dortmund, Germany: Spiekermann & Wegener Urban and Regional Research. Retrieved from http://www.spiekermann-wegener.de/mod/pdf/AP_1101_IRPUD_Model.pdf

Wegener, M. (2011b). From macro to micro — how much micro is too much? *Transport Reviews, 31*(2), 161–177.

Wegener, M. (2013). The future of mobility in cities: Challenges for urban modelling. *Transport Policy, 29*, 275–282. Retrieved from http://www.spiekermann-wegener.de/pub/pdf/MW_WCTR2010_01651.pdf

Wegener, M. (2014). Land-use transport interaction models. In M. M. Fischer & P. Nijkamp (Eds.), *Handbook of regional science* (pp. 741–758). Heidelberg/New York/Dordrecht/London: Springer.

Wuppertal Institute for Environment, Climate and Energy. (2017). Framework Program for the Implementation of the Energy Transition in the Municipalities of the Ruhr Area. Retrieved from http://www.energiewende-ruhr.de/