

Actors and factors in land-use simulation: The challenge of urban shrinkage

Dagmar Haase^{a,b,*}, Annegret Haase^b, Nadja Kabisch^{a,b}, Sigrun Kabisch^b, Dieter Rink^b

^a Humboldt University Berlin, Institute of Geography, Rudower Chaussee 16, 10099 Berlin, Germany

^b Helmholtz Centre for Environmental Research, UFZ Department of Computational Landscape Ecology, Permoserstr. 15, 04318 Leipzig, Germany

ARTICLE INFO

Article history:

Received 5 April 2011

Received in revised form

9 February 2012

Accepted 11 February 2012

Available online 17 March 2012

Keywords:

Social simulation

Land-use modeling

Urban shrinkage

SD

CA

ABM

ABSTRACT

Both modelers and social scientists attempt to find better explanations of complex urban systems. They include development paths, underlying driving forces and their expected impacts. So far, land-use research has predominantly focused on urban growth. However, new challenges have arisen since urban shrinkage entered the research agenda of the social and land-use sciences. Therefore, the focus of this paper is a twofold one: Using the example of urban shrinkage, we first discuss the capacity of existing land-use modeling approaches to integrate new social science knowledge in terms of land-use, demography and governance because social science models are indispensable for accurately explaining the processes behind shrinkage. Second, we discuss the combination of system dynamics (SD), cellular automata (CA) and agent-based model (ABM) approaches to cover the main characteristics, processes and patterns of urban shrinkage. Using Leipzig, Germany, as a case study, we provide the initial results of a joint SD-CA model and an ABM that both operationalize social science knowledge regarding urban shrinkage.

© 2012 Elsevier Ltd. All rights reserved.

1. Introduction

Land-use modeling has used cities as objects for a long time. The dominant understanding of cities by modelers is that of a complex system including properties such as emergence, self-organization and non-linear dynamic behavior (a.o. Schaldach et al., 2011; Berling-Wolff and Wu, 2004; Barredo et al., 2003; Ravetz, 2000). Social scientists define cities as a specific type of settlement that contains a large population, much diversity of land-use and a dense, built-up area. Their focus is on actors, in particular their socio-economic and socio-demographic features, their specific attitudes concerning housing environment and their interactions within institutions and governance structures (Storper and Manville, 2006). The interlinkages among built, social and environmental components determine both the complexity and dynamics of urban development (Kasanko et al., 2006). Both modelers and social scientists seek a better understanding of these complex urban systems in terms of their past and future development paths, the underlying forces that drive them and the interactions (including mutual feedback) between built environment and urban society (Noordwijk et al., 2011; Sterk et al., 2011).

Rapid urbanization and population growth currently dominate the scientific debate because they lead to significant changes in land-use and to environmental decline (Nuissl et al., 2008; Banzhaf et al., 2007; Cheng and Masser, 2003). The assessment of impacts related to urban growth, such as increases in sealed surfaces, urban sprawl, traffic congestion and residential segregation, is important and necessary, not only for understanding environmental impacts but also to support the implementation of more sustainable forms of urban development (Kazepov, 2005; Han et al., 2009). However, new challenges are arising because urban growth no longer represents cities' exclusive development path (Turok and Mykhnenko, 2007; Kabisch and Haase, 2009). Urban shrinkage is a development path that is spreading widely across the world (Oswalt and Rienets, 2006). The process has started, for example, in Europe's old industrial regions (Northern England, the Scottish Clyde side, Lorraine, the Rhine-Ruhr area), in large portions of European post-Socialist countries (Großmann et al., 2008; Kabisch, 2007) and in the "rust belt" in the US (Beauregard, 2009; Blanco et al., 2009). Recent shrinkage has also occurred in Japanese and South African cities (Rienets, 2006).

Shrinkage is not a new phenomenon insofar as that it already occurred during economic crises, wars, revolutions and systemic transformations, as well as epidemic or hazard catastrophes with subsequent population losses (Rienets, 2009). As a lasting worldwide phenomenon, shrinkage has become a challenge for urban policy and planning. Local political leaders and planning

* Corresponding author. Helmholtz Centre for Environmental Research, UFZ Department of Computational Landscape Ecology, Permoserstr. 15, 04318 Leipzig, Germany. Tel.: +49 341 2353950.

E-mail address: dagmar.haase@ufz.de (D. Haase).

officials find urban shrinkage difficult to manage; in many places, local leaders are simply unable to cope with it (Jessen, 2006).

Social science has made considerable progress in recent years in understanding the specific constellations of drivers and effect chains produced by shrinkage to urban systems. However, considering the dynamic societal, demographic and economic conditions at present, urban shrinkage is an under-researched process in land-use modeling. In order to discuss the future of currently shrinking cities, there is a need for more appropriate modeling approaches and more suitable indicators to grasp the causalities and spatial consequences of urban shrinkage.

Set against this background, the focus of our paper is twofold: First, we call for an interdisciplinary approach involving urban modeling and social science. Acknowledging the fact that scientists have identified the need to improve the integration of the social sciences and land-use modeling to achieve a balanced method of “leaping together” (Oxley et al., 2004; Costanza, 2003), we show a way to integrate social science knowledge into the modeling of urban shrinkage from the very beginning of the study. This approach entails the commonly employed research focus of a coupled qualitative-quantitative methodological design that includes the appropriate data as well as the critical appraisal of preliminary results. Social science knowledge provides novel and detailed information about the “real world of shrinkage” (Kabisch et al., 2006) that serves as an essential source of data for a shrinkage model.

Second, we present a concept that proposes the combination of SD, cellular automata (CA) and ABM approaches, thereby bringing together different subsets. We believe that creating specific combinations (loose or tight) of at least two of these three approaches is the best way to comprehensively simulate urban shrinkage without neglecting the achievements in urban modeling.

For application, we use a case study of Leipzig, Germany. We chose Leipzig because it is one of the few European cities that exhibit long-term shrinkage (Turok and Mykhnenko, 2007). Its population declined from a peak of 713,000 inhabitants in 1933 to 437,000 at the end of the 1990s (Doehler and Rink, 1996). In particular, the accelerated shrinkage during the 1990s, which was due to out-migration, demographic change and suburbanization, has led to an enormous vacancy rate of 20% of the total housing stock, or approximately 62,500 vacant flats in 2000 (Municipality of Leipzig, 2006). In addition, the emergence of brownfields, which arise from deindustrialization and demolitions, as a mass phenomenon in the inner city, along with the construction of new housing and commercial estates in the outskirts, has led to a “perforated” urban fabric (Couch et al., 2005; Lütke-Daldrup, 2003). Furthermore, there are several land-use models available for Leipzig (Haase et al., 2010; Lauf et al., 2012a,b; Petrov et al., 2009). Finally, the social scientists among the authors have thoroughly analyzed this case study (Rink et al., 2009). In our paper, we will draw conclusions for the Leipzig case study, as well as for our modeling solution for shrinking cities in general, by discussing the case study’s results in the context of studies of other shrinking cities across Europe.

We structure the paper as follows. In Section 2, we begin by describing the phenomenon of urban shrinkage in more detail and illustrate its impact on urban land-use in particular. In Section 3, we provide a short review of different approaches to modeling urban systems and urban land-use, with a particular focus on their integration of social sciences. In Section 4, we discuss, through the Leipzig case study, the opportunities and limits of an integrated modeling approach and its transferability to comparable urban settings. In Section 5, we provide the conclusions from our study.

2. Urban shrinkage: causes and consequences

Shrinkage has been discussed under the label of “urban decline,” meaning wider shifts in the spatial organization of urban regions (van den Berg et al., 1982; Lever, 1993; Garreau, 1991). Shrinkage has been examined through the lens of uneven economic development (Harvey, 2006) and the underlying dynamics of the territorial division of labor (Amin and Thrift, 1994; Storper, 1995), and also as a consequence of demographic change (Müller, 2004). We define urban shrinkage as a phenomenon resulting from the specific interplay of different macro-processes operating at the local level (Rink et al., 2009; Moss, 2008).¹ Macro-processes encompass developments in the economic, demographic or settlement systems, environmental hazards and changes in the political or administrative system (such as the systemic changes in Eastern Europe coupled with the introduction of a market economy). The current processes determining shrinkage emerge in the form of the decline of traditional industries, a decline that induces general economic crises, unemployment and out-migration to other prospering regions. Furthermore, rampant suburbanization leads to residents abandoning the city. Both processes often rapidly cause an increase in the age of the remaining population, resulting in further demographic decline (Couch et al., 2005; Nuissl and Rink, 2005; Kabisch et al., 2008).

Population decline has impacts on business and employment, housing, social and technical infrastructure, municipal finances, social cohesion, segregation and other aspects of urban life (Oswalt and Rieniets, 2006; Großmann et al., 2008). Urban shrinkage results in a mismatched supply and demand of space and infrastructure. In this regard, urban shrinkage also leads to a reconfiguration or reshaping of urban land-use structures or patterns. On the one hand, it leads to vacancies and decreasing cohesion in the affected neighborhoods; on the other, it permits a redistribution of households according to their current housing preferences because of low housing costs in favored inner-urban locations. Clearly then, shrinkage can greatly affect the quality of urban life (Fritsche et al., 2007) and fuel both decline (and further out-migration) and resurgence (Kabisch et al., 2009).

Urban shrinkage reshapes the social settings for the actors affected: residents, planners, policy makers, entrepreneurs, and service suppliers (Haase et al., 2007; Jessen, 2006). It is difficult to steer or govern urban shrinkage because under the conditions it produces, governance arrangements risk becoming unstable and fragmented due to a high dependency on external funding, a funding-dependent restriction on initiatives and unstable coalitions among weak actors (Couch et al., unpublished). In our understanding, the process of shrinkage relates to population decline as such and not, as is widely discussed in American debates, to sharp ethnic or racial segregation.

2.1. Urban shrinkage as a challenge for land-use change

The impact of shrinkage on land-use is rather complex because it affects both urban fabric and open space in a very uneven manner. For example, many cities in the U.S. experience the so-called “doughnut effect” due to the suburbanization; whereas the city centers become “hollows,” consisting of brownfields and unused plots, the suburbs grow. In Eastern Germany, urban shrinkage has led to a “perforation” of the urban fabric wherein parts of the city face a more drastic disappearance of land uses

¹ While single macro-processes sometimes are predominant in a particular setting, in other settings it is difficult or almost impossible to work out any hierarchy among them.

(Lütke-Daldrup, 2003). In Eastern Europe, despite the emergence of brownfields as consequence of deindustrialization, we have not been able to notice major land-use changes arising from shrinkage until now.

The impacts of shrinkage on land-use can lag; for instance, it takes time until a vacant building is demolished or a new land-use is finally established. Often, we observe various kinds of interim uses, which represent the subtler processes of land-use change. Compared to growth, urban shrinkage is less predictable. The same is true for planning or governance of shrinkage because of the phenomenon's unstableness and uncertainty. Nevertheless, urban shrinkage is not only associated with losses; it also creates more living and open spaces, along with affordable land for new use and investment.

Population loss leads to a decrease in residential density and to both oversupply and underuse of urban land, namely housing stock, infrastructure and services (Haase et al., 2007). This creates problems for both public and private suppliers with respect to the underuse of building stock, primarily dense urban fabric (multi-story, old, built-up stock, prefabricated housing estates from a period of state socialism and estates constructed after 1990), lower density estates (single or detached houses), industrial buildings and storage depots. Underuse, in turn, leads to housing and commercial vacancies and to a more rapid dilapidation of unused buildings (Bernt, 2009). While in some places, buildings are demolished to “balance” the housing or real estate market (Couch et al., 2005), in others they simply become unusable after a period of disuse (for eastern Germany, see Nuissl and Rink, 2005; for Pittsburgh, see Großmann, 2007). While a decreasing building stock density may lead to a “relaxation” in a densely built city, at a later stage such a decrease might, because of the vacant lots, lead to a fragmentation and even perforation of the urban space in the form of a dissolution of the street or block structure (Haase et al., 2007).

Table 1 shows a detailed overview of the drivers of, and impacts on, urban shrinkage. It provides a short explanation of the underlying processes (as gathered through in-depth interviews by the authors). The detailed characterization of the specific shrinkage processes shows that these processes are interrelated and shape the specific form or trajectory of shrinkage in a particular city (in our example, Leipzig).

Table 2 lists those land-use classes that have to be implemented in a coupled, spatially explicit model of urban shrinkage.

Fig. 1 illustrates the cause-effect relationships among the variables compiled in Table 1, aggregating them into cause-effect chains of urban shrinkage. According to the authors, such complex conceptual models for urban shrinkage have yet to be developed until now. The diagram is the first step in preparing and implementing the quantitative modeling solution. As such, the diagram approximates the systemic complexity and emergence of the urban shrinkage process; that is, it incorporates feedback from the various elements of the shrinkage process. One cumulative, positive feedback loop connects ageing, changing population age and class structures and population loss. Another positive feedback loop presents ageing followed by an increase in socio-spatial fragmentation and segregation, a concentration and deconcentration of households in distinct areas (small-scale fragmentation), a demolition of the vacant stock, the ensuing formation of urban brownfields and a subsequent perforation of the housing stock (Lütke-Daldrup, 2003). These processes may foster out-migration by those who do not want to live close to dilapidated building stock or overgrown brownfields (so-called “urban wilderness” Rink, 2009). Here, the vicious cycle of shrinkages becomes very clear. The diagram also shows the potential benefits of shrinkage such as transitory housing becoming affordable due to an oversupply of

Table 1
Processes, patterns of urban shrinkage and their social science explanation.

Processes	Social science explanation
Decrease in density	<ul style="list-style-type: none"> Population loss leads to decrease in residential, commercial and other land-use densities
Increase in housing and commercial vacancies ^a	<ul style="list-style-type: none"> Decreasing demand leads to supply surplus and an underuse of housing and commercial stock
Underuse of infrastructures	<ul style="list-style-type: none"> Population losses and decrease in densities lead to decreasing demand and underuse of infrastructures such as schools, kinder-gartens, public transport etc. Higher costs through maintenance of surplus infrastructure or closure/demolition
Increase of unused urban land	<ul style="list-style-type: none"> Consequence of decreasing demand and underuse Refers to built and un-built urban land, last mentioned may turn to be “new urban wilderness”
Perforation of urban structures	<ul style="list-style-type: none"> Demolition, abandonment and underuse lead to the dissolution of the street or block grid of a city or urban area Perforated areas are characterised by a large percentage of vacant areas within an urban territory or city
Changing socio-demographic structure of population	<ul style="list-style-type: none"> Population losses and selective out-migration lead to ageing, changing household structures and a “blurred” age group distribution
Shrinkage of the local labor market	<ul style="list-style-type: none"> Decrease in employment and jobs leads to increase in post-industrial brownfields and decrease in demand for urban land for economic and commercial uses
Increase in socio-spatial fragmentation and residential segregation	<ul style="list-style-type: none"> Selective out-migration leads to a “blurred” socio-economic structure of remaining inhabitants and brain drain Disadvantaged population concentrates in dilapidating areas with high housing vacancies Shrinking/resurging areas in close neighborhood
Change in housing mobility within the city and its region	<ul style="list-style-type: none"> Oversupply of housing in combination with moderate housing costs leads to higher housing mobility and a greater choice for various residential groups Level of housing mobility may increase due to greater choice and moderate housing costs Opportunity for transitory housing
Decrease in municipal budget	<ul style="list-style-type: none"> Decrease in tax revenues as a consequence of population losses results in many cases in rising expenses and increasing dependency on external money
Need for new planning schemes	<ul style="list-style-type: none"> Growth-oriented planning schemes must be replaced by a strategy that aims at coping with urban shrinkage

Source: authors' research.

^a *Housing and commercial vacancies* = housing and commercial stock that is inhabitable and useable, but not inhabited or used; *Perforation* = dissolution of the street or block grid of a city or urban area due to vacant lots and brown- or green fields that separate or divide built lands.

flats. There are also “dead ends” in the diagram such as the need for new planning schemes that may lead to urban shrinkage; however, insufficient empirical evidence exists to verify this loop.

The diagram in Fig. 1 explains shrinkage specifically for the sample site at Leipzig; not all of it necessarily applies to other shrinking cities, but it is largely applicable. Generally, we emphasize

Table 2

Land-use classes to be implemented in a coupled spatially explicit model of urban shrinkage (the land use classes discussed in detail are marked grey).

Land use class	... including	Process/State
Dense urban fabric	Old built-up tenements Social housing from the 1920–1930s State socialism period prefabricated estates Residential parks	Infill, fall vacant, demolish, create
Low-density urban fabric	Single houses Detached houses Villas	
Commercial land	Industrial buildings Storage depots Garages	
Brownfields		
Urban green	Parks Lawns Forests Arable land Sport, leisure	Create, disappear
Social infrastructure	Kindergarten, schools Homes for the aged	Develop, close
Provisioning infrastructure	Electricity supply Water supply	
Transport infrastructure	Railway Tram Roads	

that comparative studies of the commonalities and differences among the trajectories of shrinking cities rarely address contemporary conditions. At present, a EU 7 FP project titled “Shrink Smart – The Governance of Shrinkage within an European Context” (5/2009–4/2012) is gathering evidence from seven European cities (see also Rink et al., 2009 and www.shrinksmart.ufz.de).

3. What urban land-use change models offer

Scholars and practitioners use urban modeling to simulate the dynamics of urban development and to obtain a better understanding of the factors that drive these dynamics. To assist urban planning, scholars have developed a range of models simulating urban land-use changes (EPA, 2000; Agarwal et al., 2002; Timmermans, 2003; Berling-Wolff and Wu, 2004; Verburg et al., 2004; Hunt et al., 2005; Axhausen, 2006; Beckmann, 2006; Geurs and van Wee, 2004; Matthews et al., 2007; Wickramasuriy et al., 2011). These models range from generic tools to specific case studies of a variety of urban regions. The models differ largely with regard to their structures, their representations of land-use and human decision-making and their implementation.

A brief review of three different modeling approaches – SD, CA and ABM – illustrates the advantages and disadvantages of these simulation models. We chose the SD, CA and ABM approaches because they take into account causal relationships as well as the feedbacks between the impacts and driving forces within urban land-use changes. This allows us both to integrate social science dimensions and to consider urban systems in a spatially explicit fashion. We present the advantages and disadvantages of each approach. We do not consider other models, such as transport models (reviewed in Geurs and van Wee, 2004), economic models and integrated urban land-use transportation models,² because of the specific advantages of the three aforementioned approaches.

3.1. System dynamics

SD is a top-down approach that many studies have applied because of its ability to include and analyze socio-economic forces in the simulation. The classical urban SD model, as described in Sanders and Sanders (2004) citing Forrester, includes three subsystems (business, housing and population) and detailed sub-models. Later, SD was used to simulate urban landscape change (Dhawan, 2006; Sterman, 2002) and to analyze land-use changes (Li and Liu, 2007), especially urban growth (He et al., 2006; Han et al., 2009). SD typically consists of stocks and flows, including interdependencies, non-linear responses, irreversible changes, long lag times and interactions of local systems (Theobald and Gross, 1994). SD can include changing behavior patterns in complex, dynamic systems and can therefore handle large stocks of temporal data. The model describes the behavior of a complex system, such as an urban landscape, using differential equations. Through its capacity to include feedback loops, functional relationships can change dynamically during the simulation. Therefore, SD is up to the challenge of simulating household-related residential demands under urban shrinkage conditions; when socio-demographic structures change, SD is able to simulate how much land or housing is required or becomes vacant in the city and in neighboring suburban areas.

However, SD does not reveal the spatial pattern of land-use changes, meaning that it does not incorporate spatial variables that influence and drive urban land-use change. Thus, in the case of shrinking cities, the allocation of urban brownfields or vacant housing cannot be shown in a spatially explicit way. A few models already incorporate at least some elements of urban shrinkage, such as demographic decline and its impact on residential land development, as single variables and processes, but they do so only to a limited extent (Lauf et al., 2012a,b; Haghani et al., 2003a,b; Eppink et al., 2004; Sanders and Sanders, 2004).

Finally, through different “what-if” scenarios, SD models can predict changes in complex systems. This capacity is useful in the process of recommending and examining policy decisions (Han et al., 2009), which are of high importance in shrinking cities (e.g., when counteracting the decline of the labor market).

3.2. Cellular automata

CA gained popularity in land-use modeling because they offer a technique suitable to the simulation of complex systems emerging within a spatial environment. Such methods are strongly consistent with Geographical Information Systems (GIS) and enable us to model land-use changes (Clarke and Gaydos, 1998; White and Engelen, 2000), especially spatial urban growth and urban sprawl (Batty and Xie, 1994; Couclelis, 1997; Batty et al., 1999; Sui and Zeng, 2001; Van Vliet et al., 2009; Petrov et al., 2009). More recently, scholars have applied constrained CA models to support land-use planning and policy analysis (e.g., Itami, 1994; Sui and Zeng, 2001; Geertman and Stillwell, 2004; Delden et al., 2008) and to develop future scenarios (Barredo et al., 2003). In particular, scholars have used modified standard CA as modeling tools for urban process simulation (Sui and Zeng, 2001; Barredo et al., 2003). The main characteristic of process-based CA (the bottom-up approach) is that it consists of a grid of cells exhibiting complex global behavior that emerges from simple, local rules describing how each cell changes in response to its neighbors during a discrete time step (Couclelis, 1985; Fang et al., 2005).

The CA approach can be easily implemented using remote sensing and GIS data (Han et al., 2009; Schnase et al., 2003), and thus, modelers often use it because it provides a way to model and express both spatial and temporal variations. In the case of urban

² Such models are, e.g., MEPLAN (Abraham, 1998) and TRANUS (De la Barra, 1989). They have been applied as market-based urban models that use zones and networks.

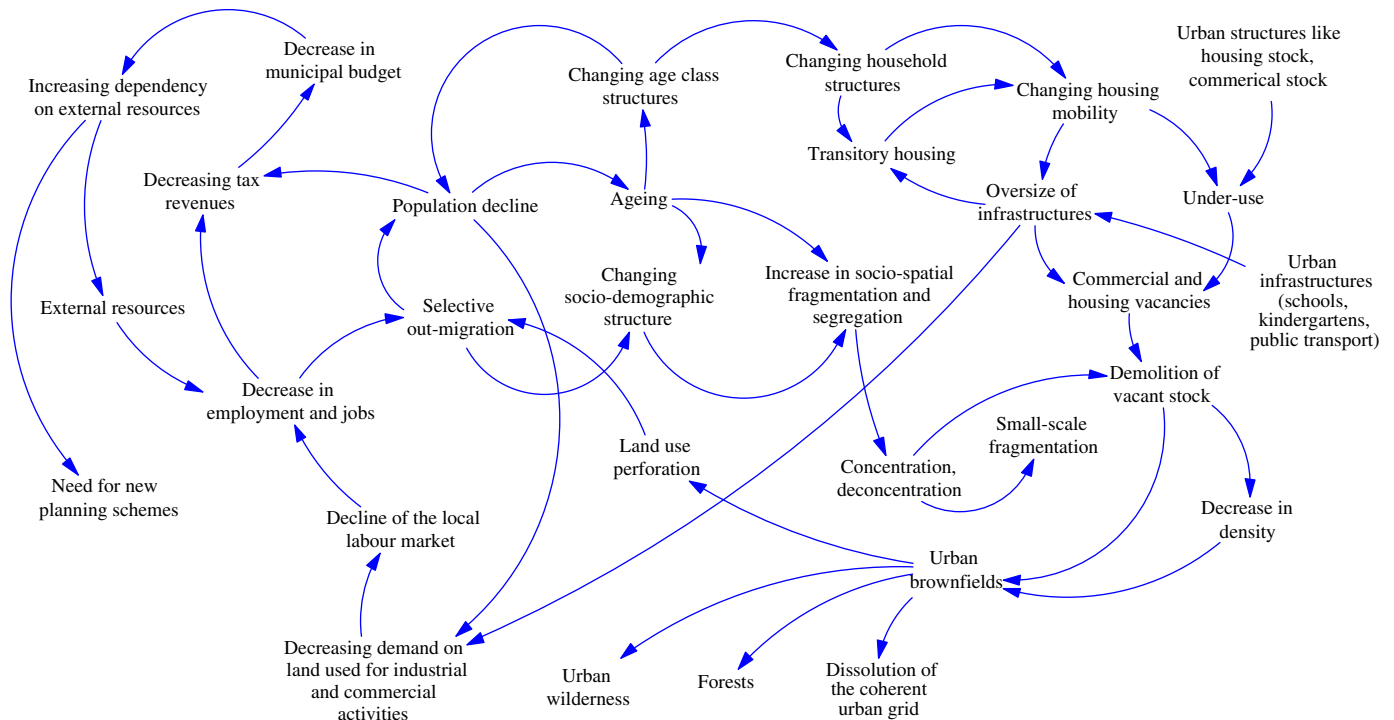


Fig. 1. A conceptual relational model that displays the causal relationships between the variables of shrinkage (namely its drivers, processes and impacts) which are shown in Table 1 (content: A. Haase, D. Rink; model: D. Haase).

shrinkage, CA is able to show these variations in the urban area, e.g., developing residential and commercial vacancy or perforation over time. In addition, neighborhood perceptions and accessibility can be simulated because they are particularly observable in shrinking areas.

However, the CA approach is limited because scientists cannot drastically modify rules during the simulation (Theobald and Gross, 1994). This approach also fails to capture interactions between socio-economic factors (e.g., decline of the labor market and subsequent population decline) and doesn't include local and regional interactions between two or more urban areas. Finally, the CA approach does not incorporate individual or household decision-making (e.g., residential decisions driven by urban decline or rising prices) as feedback (Haase et al., 2010; Li and Liu, 2007). In the context of building a more comprehensive urban land-use change model that includes growing and shrinking areas, the CA approach is best suited to studying the allocation of land-use demands within an integrated modeling approach (Fang et al., 2005; Han et al., 2009).

3.3. Agent-based models

Many scholars in the social sciences use ABM to simulate individual decision-making (Epstein, 1999), as well as for land-use modeling (Waddell, 2002; Parker et al., 2003; Lagabriele et al., 2010). ABM techniques are suitable for simulating social processes such as residential development involving several agents, that shape an urban society (Li and Liu, 2007; Ligtenberg et al., 2008; Haase et al., 2010; Le et al., 2012). ABM models the interactions between both human and land-use systems by defining different decision-making agents (modeling units and behavior models). Agents can have different properties and strategies, and they can interact with other agents and with their environment (Bonabeau, 2002; Sawyer, 2003). In terms of shrinkage, agents can determine out-migration and vacancies through individual

preferences and decision-making. Moreover, the new planning and governance structures that develop in shrinking cities represent collective decision-making processes. So far, scholars have developed spatially implicit and explicit approaches using different modeling environments such as Repast, NetLogo or Swarm (Matthews et al., 2007; Valbuena et al., 2008; Verburg, 2006; Fontaine and Rounsevell, 2009).

However, the use of the ABM approach to modeling urban processes, especially shrinkage, is still in its initial stages, particularly because of the missing empirical foundation for translating actors' complex behavior into rules for the model (Li and Liu, 2007). A first approach to simulating resident agent behavior for an entire city, RESMOBcity, was successful and exemplified the residential mobility of households in Leipzig (Haase et al., 2010). We will refer to the RESMOBcity model when we discuss the model development later in this paper (Section 4).

In conclusion, each modeling approach reviewed in Section 3 offers specific strengths and weaknesses for modeling shrinkage. Consequently, the strategy of combining components of SD, CA and ABM, which includes a strong linkage to social science expertise, appears the most promising (cf. also a review by Haase and Schwarz, 2009). Table 3 summarizes the features of urban shrinkage and the proposed modeling approaches to be combined. It shows that all three models are appropriate for simulating specific aspects of shrinkage and highlights the relative advantages and constraints of each model type.

4. Integration of approaches to modeling urban shrinkage

4.1. A shrinkage model "ingredients"

As discussed in Section 2, urban shrinkage causes new challenges for the simulation of urban land-use change because most of the existing models were developed to study urban growth (Schwarz et al., 2010). Urban shrinkage requires detailed attention

Table 3
Features of urban shrinkage and respective suitable modelling approaches.

Features and processes of urban shrinkage	Modelling approach	Data availability	Spatial resolution of data	Advantages
Population loss	SD ^a	Annual	Local Municipal Districts	<ul style="list-style-type: none"> • Large stocks which create demands on space but whose dynamics can be modelled neglecting the space
Socio-demographic structure		Annual	Local Municipal Districts	<ul style="list-style-type: none"> • Fast processing • Many existing numeric models
Households and forms of cohabitation				
Housing demand	SD ^a or ABM ^c	Annual	Aggregated value at city level	<ul style="list-style-type: none"> • Creation of stocks and flows of land demand for a population (eg households)
Segregation	ABM ^c	Annual	Local municipal districts	<ul style="list-style-type: none"> • Captures individual decision-making processes
Urban structures: housing stock, commercial land	CA ^b	No time restriction	Remote sensing data, biotope maps, Google, ATKIS ^a	<ul style="list-style-type: none"> • Properties of the space • Neighborhood relations • Accessibility dependencies • Density as property of space
Residential and commercial vacancy		Irregular	Estimates by city government and housing companies	
Perforation		No time restriction	Derived value from land-use	
Underuse of infrastructure		Annual	Database of municipal water, energy and transport supply	
Decline of the labor market	SD ^a	Annual	Local municipal districts	<ul style="list-style-type: none"> • Cumulative stocks • Fast processing necessary • Many existing statistical and econometric models as knowledge base
Decline of tax revenues		Annual	Aggregated value at city level	
Decrease of municipal budget		Annual	Aggregated value at city level	
Need for new planning schemes and governance structures	ABM ^c	Irregular	Both local municipal districts and aggregated at city level	<ul style="list-style-type: none"> • Captures individual and collective decision-making processes • Need for comprehensive “agent profiles” to depict cases such as the prisoner’s dilemma or collaboration

^a System dynamics.

^b Cellular automata.

^c Agent-based model.

to how population decline becomes the driving force of land-use change (this is necessary for modeling growth as well). Additionally, models must include de-densification, land-use perforation, the simultaneity of underuse and abandonment as well as new land consumption, a process that often occurs in shrinking cities and that represents an extremely unsustainable pathway for resource use (Rink et al., 2009). Moreover, models must incorporate the specific housing allocation behavior of households in shrinking cities, be it a higher residential mobility stemming from the surplus supply of housing or in/out-migration related to dilapidation and decay in certain areas of the city (Haase et al., 2010).

Using new social science knowledge (such as that presented in Section 2 and conceptualized in Fig. 1), modelers must specify newly defined feedback loops between supply and demand for residential and commercial areas and related housing preferences and prices (including the impact of vacancies) Models have to allocate the impact of housing and commercial vacancies, underused urban patches and brownfields into CA or agents’ preference profiles (ABM). Furthermore, simulation models covering urban shrinkage must integrate socio-economic variables, such as the underuse of infrastructure (transport, educational and social facilities), the dropping of flat, house and land prices on the rental market, the decline of the labor market and a decrease in municipal budgets and tax revenues related to population and labor facility loss (Rink et al., 2009). On the governing side, empirical studies have uncovered evidence that urban shrinkage leads to new planning schemes, governance structures and hierarchies of collective decision-making (Bernt, 2009; Jessen, 2006); this needs to be incorporated as well.

4.2. A procedure for an integrated model

As argued in Section 3, there are different model types suitable for representing different features of urban shrinkage listed in Table 1.

First, the SD approach can compute the population dynamics of a large number of persons and households (forming large stocks) and thus can capture age class specific population decline in a manageable way (cf. the proposed integration procedure in Fig. 2). Using a stock and flow model, we can create a number of differently composed household types with different properties and demands on the housing space. The fast processing of non-spatial SD models permits us to profile housing demand stocks in a shrinking city with respect to demographic change (Lauf et al., 2012a,b).

Second, the SD model approach can serve as the macro-model input for a CA micro-model that spatially represents the shrinking city in the form of a cellular grid of land uses. The CA micro-model translates the household housing demand into the residential space, using the outputs of the SD model about housing preferences and distributing the households throughout the urban space according to these preferences (Fig. 2). As highly preferred housing types exist next to lowly preferred ones, and as more housing space exists than households needing that space, the CA creates spatially explicit layers of built (residential, commercial) and vacant (demolished, brownfields) grid cells. The CA cells have a neighborhood properties feature that can represent the transition of land use by recategorizing individual cells from vacant to demolished (cf. Table 2 listing the respective land-use classes we propose to capture urban shrinkage for Leipzig).

Third, to represent the planning and governance of the supply and demand relations that the SD and CA models create, as well as

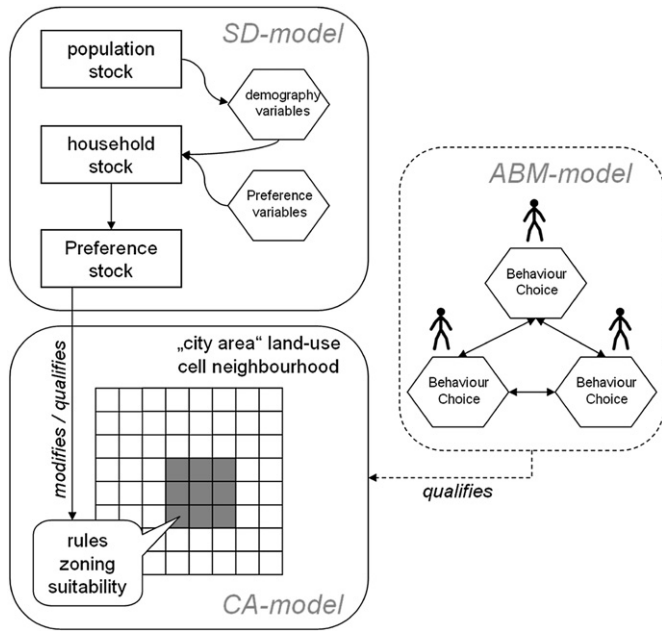


Fig. 2. Iteration of one simulation of the coupled SD-CA model including the possible extension by an ABM.

to manage the response of these “driving forces,” we must add an ABM approach. In this framework, different urban actors such as residents, planners, and developers “negotiate” new land-use patterns, space suitability and zoning in the shrinking city. Different individual and collective decision-making processes gleaned from qualitative social science research and interviews with decision-makers might run in one time step of the SD and CA model (normally 1 year). Agents decide upon the status of different cells and therefore create arrays of land-use change in t_{n-1} . This process (similar to the outputs of the SD model) provides input for the CA, which computes a new land-use pattern for t_n . The spatial CA land-use model provides the “ground” on which the urban agents act. Social science work delivers extensive material to describe agents, particularly the roles of housing and finance companies and forms of governance in shrinking cities (Rink et al., 2009). An ABM built for Leipzig (RESMOBcity; Haase et al., 2010) provides an initial understanding of the behavior-driven reorganization of residential vacancies in a shrinking city.

Finally, a generic, multi-ABMland that the EU-project PLUREL (Schwarz et al., in press; www.plurel.net) developed provides a framework for how urban planners, businesses, developers, municipal infrastructure and service providers, private landowners and lobbyists might interact. Based on a series of interviews carried out in the EU-projects PLUREL and Shrink Smart, we can characterize the roles of different stakeholders involved in urban shrinkage. By describing those roles using the ABM approach, we are able to deal with the diversity of the stakeholders involved. Still, the empirical knowledge of Shrink Smart needs to be implemented into the ABMland.

4.3. Advantages and challenges of such an integrated model

To create a more comprehensive method combining the advantages of the modeling approaches discussed so far, we call for an integrated modeling approach consisting of at least two of the three models: SD, CA and ABM. The integrated approach fits better because shrinkage is a complex process that includes interlinked, heterogeneous features and patterns. This approach integrates SD to compute the population dynamics of a large number of persons

and to create indicators of housing demand (forming stocks) for the shrinking population and new household compositions. This approach also uses CA to make the stocks and flows of population and household demands spatially explicit and an ABM to incorporate the decision-making of various urban stakeholders and governance structures. We use the SD technique to compute quickly large stocks of space demand. We use the ABM approach to incorporate complex and individual decision-making regarding space. The results of both SD and ABM approaches feed an “advanced” CA – the shrinking city – that simulates land-use change under conditions of urban shrinkage. We propose a loose coupling (input–output), which avoids problems in spatial unit (geometric) coupling and utilizes the advantages of fast SD model processing for population growth and the CA’s spatial representation for land-use allocation.

As a “proof of concept,” we proceed to present a first attempt at a combined SD-CA model approach along with the results of an ABM for Leipzig to illustrate the relevance and complementarity of all three approaches for the simulation of urban shrinkage.

4.4. First steps towards an integrated model: coupling SD and CA for a shrinking city

As shown in Fig. 2, an initial implementation of one part of the conceptual model demonstrates the potential of the proposed integrated approach. Using the shrinking city of Leipzig, we couple a SD population and household preference model incorporating population loss, ageing and household living preferences (leading, as argued in Fig. 1, to spatial segregation) with a CA model. The functions of the SD model, as well as its outputs, are incorporated into the log-file of the CA model (see a similar approach for Berlin in Lauf et al., 2012a,b). The log-file represents the macro-model in the Metronamica CA (Delden et al., 2005), which we used. The replacement of the original macro-model with our SD model determines that land-use allocation and transition potential are both modified and qualified by the “knowledge” of the SD model (cf. again Fig. 2). For example, whereas the original macro-model distributes new residential land-use cells/pixels according to population increase, our SD macro-model specifies population development in terms of which household types increase or decrease and which residential land-use types (cell states) they prefer. Thus, we can identify a household-driven increase or decrease of demand on new residential cells or vacant ones, which become brownfields in the next time step.

To show the benefits of replacing the original macro-model with our SD model, we utilize a null model, which uses the original macro-model and statistical data to determine trends in population, jobs and respective cells/pixels of urban land. By contrast, the coupled model uses the results of the SD model as a macro-model for the CA (see Figs. 3 and 4).

For the application phase, we used a merged dataset, including Corine land cover data (100 × 100 m) and cadastral data (1:25,000), to achieve the best representation of the urban land-use structure of Leipzig. The final CA model has a cell size of 50 × 50 m. We performed the calibration with a data time series of 1990, 1997 and 2000. We ran the model calibration from 1990 to 2000. A land-use map of 2003 was used for validation and quality assessment. For quality assessment, we chose the well-established and often used Kappa, k-Loc, k-Histo and Fuzzy kappa values (a.o. Van Vliet et al., 2009; Barredo et al., 2003). The quality assessment is given for the following land-use classes: “dense urban fabric”, “low-density urban fabric”, “commercial land”, and “brownfields”. We compared the observed data from 2003 to (1) the null model and (2) the coupled SD-CA model (Table 4).

Table 4 shows that the coupled SD-CA model consistently reports higher values for all coefficients. Consequently, when we

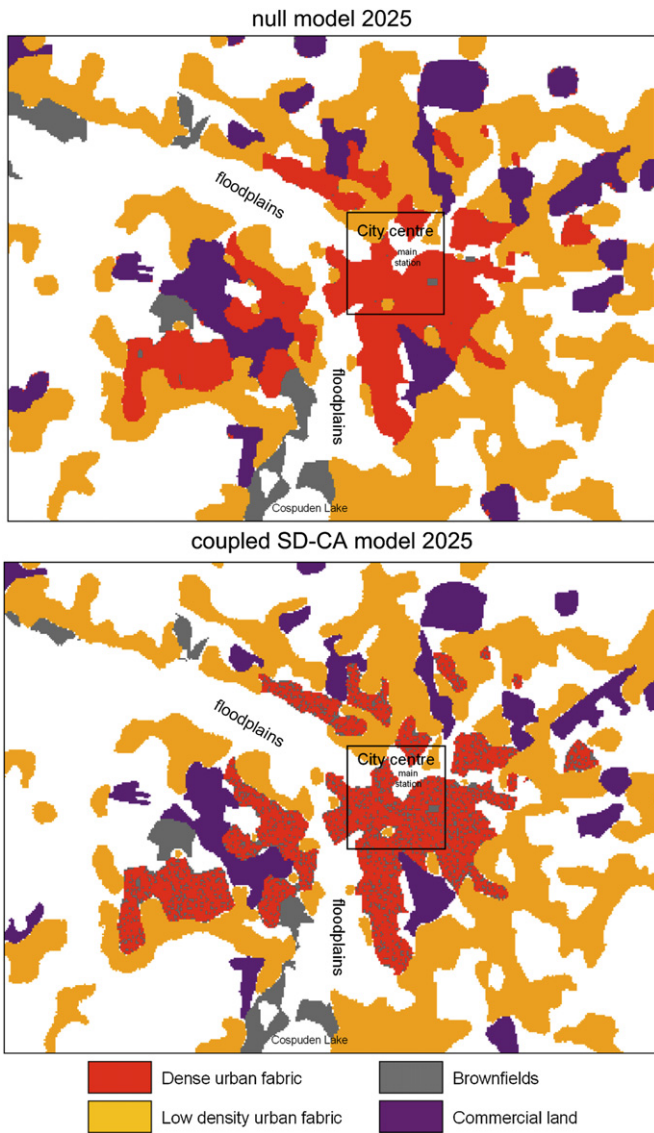


Fig. 3. Map comparisons of the 2025 simulation results for the city of Leipzig, the null model (above) and the coupled SD-CA model (below). Main geographic benchmarks of Leipzig are given for better readability of the map.

compared the Fuzzy kappa values (which express the fuzziness of the correspondence in the land-use categories between the model’s result and the reference data; Barredo et al., 2003) of the coupled model with those of the null model, the values of the coupled model were higher. This means that the coupled SD-CA model performs better than the null model with regard to the observed data.

Table 5 presents the first results of the land-use simulation to the year 2025 using both the null and the coupled SD-CA. As the SD model results determine the initial cell states of the CA, both models differ in terms of their initial data. Whereas the null model overestimates the initial data for “dense urban fabric” by almost 8% compared to the observed data in 2000, the coupled model starts with less than a 2% deviation from the observed data (land-use map of 2003). The same is true for the land-use class “lower density fabric”. Whereas the null model overestimates the number of cells by about 5%, the coupled model starts with values with almost no deviation from our findings in the observed land-use map of 2003.

Figs. 3 and 4 show the simulation results. When we first compare the final simulation maps of 2025 for Leipzig, we find clear

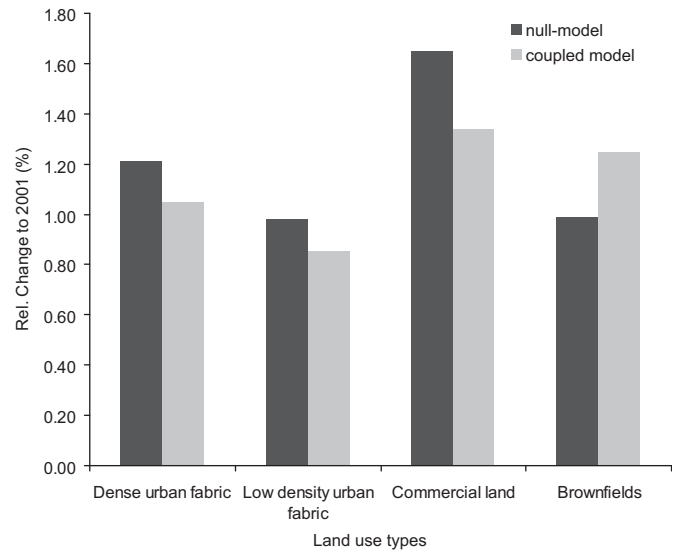


Fig. 4. Relative change (%) of the results of the null model and the coupled SD-CA approach for four land-use classes, shown the end year of the simulation 2025 compared to the start year of the simulation 2001.

differences in both the amount and the allocation of the “dense” and “low-density” urban fabric. The same is true for brownfields. Whereas the null model shows a comparatively homogeneous pattern of dense and low-density urban fabric, the coupled model reports a vast and heterogeneous expansion of brownfields within the dense urban fabric. This finding is in accordance with observations of an increasingly perforated land-use development in Leipzig since the year 2000. The vacant plots emerge due to house abandonment within the residential, industrial and commercial areas. These then become brownfields in the majority of cases (Lorance Rall and Haase, 2011). The research reported in Section 2 made clear that there are many reasons why houses might lose inhabitants and become vacant. Thus, the high degree of heterogeneity of residential brownfields emerging in the coupled SD-CA model gives a good representation of a) the heterogeneity of the land-use perforation and b) the related uncertainty of where exactly such perforation happens. Furthermore, as shown in the coupled model, we observe stagnation in the growth of low-density urban fabric. Overall, the spatial expansion of both land-use types, dense and low-density urban fabric, remains stable since the starting year of the simulation, 2001. This is also in accordance with field observations. Thus in spatial terms, our coupled SD-CA model better represents the effects of shrinkage on land-use in the sample city.

Fig. 4 compares the results of the null model and the loosely coupled SD-CA approach for dense urban fabric, low-density urban

Table 4

Model quality assessment using the kappa, k-Loc, k-Histo and Fuzzy kappa (Fuzzy-k) values for the land-use classes “dense urban fabric,” “low-density urban fabric,” “commercial land” and “brownfields.” Observed data from 2003 is compared to both the null model and the coupled SD-CA model.

Land use class	Null model				SD-CA model			
	Kappa	k-Loc	k-Histo	Fuzzy-k	Kappa	k-Loc	k-Histo	Fuzzy-k
Dense urban fabric	0.91	0.92	0.95	0.88	0.98	0.99	0.99	0.92
Low-density urban fabric	0.89	0.91	0.91	0.88	0.98	1.00	1.00	0.94
Commercial land	0.87	0.86	0.91	0.83	0.92	0.99	0.98	0.91
Brownfields	0.71	0.72	0.91	0.81	0.84	0.97	0.92	0.93

Table 5

Initial value deviations (%) from the observed data of 2003 put into the CA for four land-use classes. The table compares the null model with the coupled SD-CA model.

	Null model	Coupled SD-CA model
Dense urban fabric	8.04	2.34
Low-density urban fabric	5.09	0.12
Commercial land	4.61	4.01
Brownfields	2.11	1.98

fabric, commercial land and brownfields. For both the null model and the coupled model, the figure displays the relative change in the values of the total number of simulated cells in 2025 with reference to 2001, the initial year of the simulation. The null model shows growth in almost all residential and industrial land uses due to the initial values of the calibration phase. In that phase, surface land uses increased regardless of population decline. However, this result is only the product of the constant downsizing of households among Leipzig's residential population and a growing number of small households (especially one-person households). This growth potential of households is limited; the "untrained" CA cannot simulate this limitation properly. Moreover, the null model does

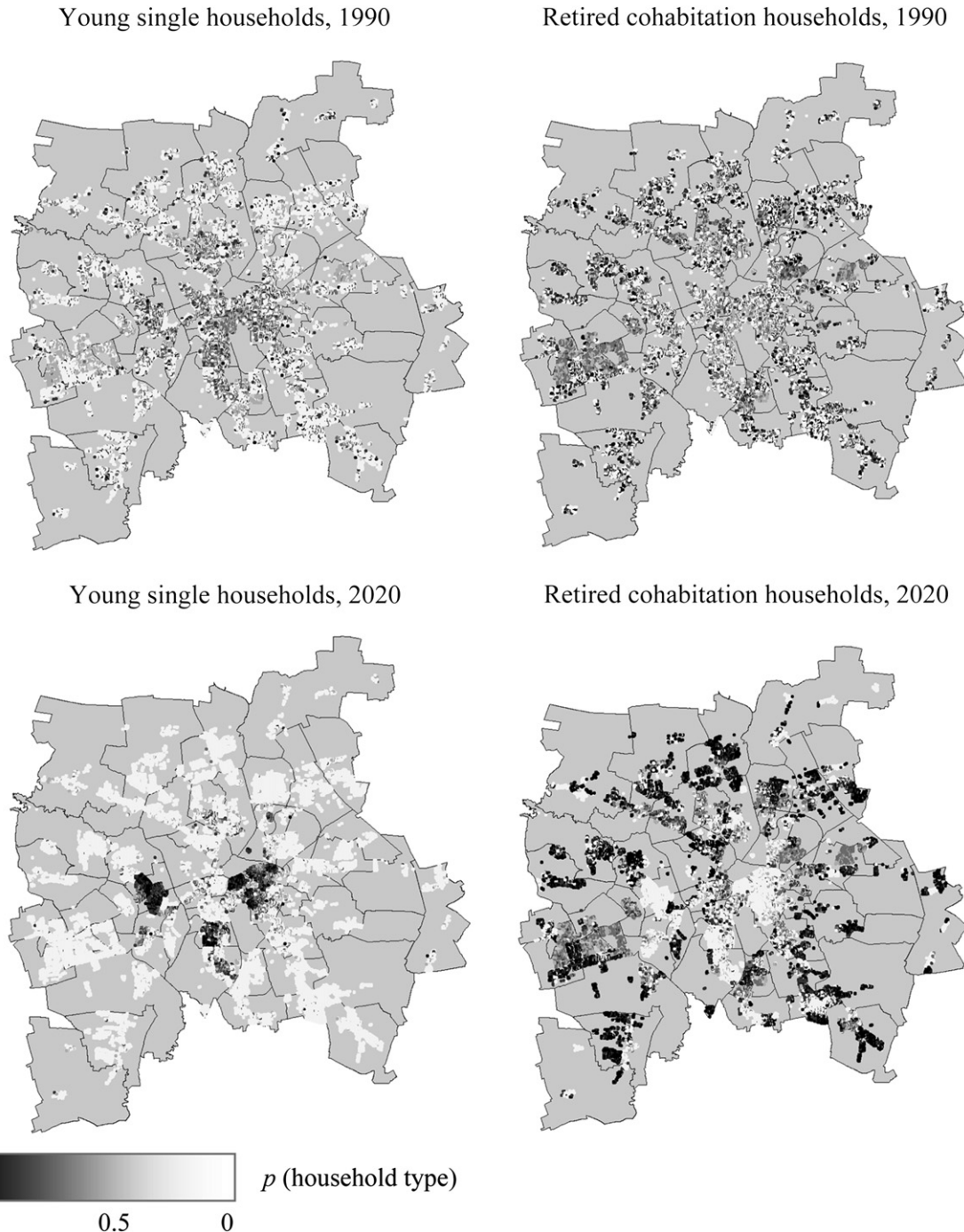


Fig. 5. Probability of the spatial distribution of young single households and retired cohabitation households in Leipzig for the two time steps of 1990 and 2020 under conditions of population decline (Haase et al., 2010; modified).

not “create” residential vacancies because it does not reflect housing decisions based on existing preferences and constraints. In contrast, the coupled model shows much more realistic developments in land use regarding settlement and industrial land-use classes. This more realistic result stems from several factors. The first is the inclusion of household development under conditions of demographic change. The second is the inclusion of housing preferences and constraints on different household types. The third is the attempt to relate all these factors to existing residential classes and, consequently, to create vacant cells that we interpret as initial brownfields.

4.5. First results of an ABM for a shrinking city

Haase et al. (2010) presented results of an ABM on residential mobility and vacancies for Leipzig. The RESMOBcity model also focuses on urban shrinkage, but from the residents’ individual perspectives. Its results show the emergent properties of the complex household migration behavior of a large city under population decline. We highlight one of the central results of RESMOBcity for this paper to illustrate that model’s potential to simulate aspects of urban shrinkage (see Section 2) and to fit its results with those of our SD-CA model. These results are also complementary in terms of what they explain. The spatial household distribution patterns simulated by RESMOBcity are in large part the result of spatial interactions between the agents (“like my neighbor”), but they also, to a limited extent, arise from factors such as distance or accessibility to social or transportation infrastructure. The functional relationship between the age structure of a population and the distribution of its households is defined by a matrix which maps the total population with n age classes to m household types. Questionnaire surveys conducted in Leipzig in several municipal local districts were used to determine the age class proportions for each of the household types. The entire procedure development of the household typification and migration behavior across the city is comprehensively described in Haase et al. (2010) and serves in this paper rather as an example which type of ABM should/will complete the coupled SD-CA model in the future.

Fig. 5 provides a representation of the spatial change in the probability of the concentration of different household types, such as young, single or retired cohabitation households, in Leipzig for a 30-year period (1990–2020).

Rather than being spread throughout the city, as they were in 1990, young singles in 2020 will primarily reside in old, but architecturally valuable, built-up districts in the inner city. This finding is in accordance with the latest federal statistics for German cities (BMVBS, 2010; Kabisch et al., 2009), and with a simultaneous decrease in young singles residing in the 1920–1930s, 1960s and GDR-era prefabricated housing estates. The model predicts a concentration of young people in the inner city, most likely because that area is close to the city center and provides better access to public transportation, labor and other socio-cultural facilities that, in turn, are supported by this influx of young people (positive feedback). By comparison, retired cohabitations will reside in the 1920–1930s, 1960s or GDR-era prefabricated housing estates because for them, lower rents and housing costs are more important than high accessibility values. The center-directed move of the younger households reinforces this process. Compared to the SD-CA model, which simulates suburban growth and inner-urban vacancies, RESMOBcity simulates an increasing segregation of the different household types in Leipzig and provides “extra” explanatory value. The ABM cannot simulate future real estate or land-use patterns, except for vacancies and vacant estates, by itself. Here, the coupled SD-CA model delivers better explicit spatial results.

5. Conclusions

This study presents an integrated approach on two levels: the combination of different modeling techniques and the inclusion of social science knowledge into modeling. First, we introduced a loosely coupled SD-CA model and an ABM in the case study of Leipzig to simulate urban shrinkage and its impacts on land-use change. In our opinion, the advantages and disadvantages of the three modeling approaches and their potential for complementary application are apparent. Generally, no single modeling approach satisfactorily answers the question of how the socio-spatial dynamics of land-use develop in a shrinking city. A combined approach, at the very least, can demonstrate the strengths of several land-use models for cases of urban shrinkage. As a result, the scope of the findings becomes wider and forms a broader foundation for debate. Moreover, the integration of different modeling approaches invites movement between different thought patterns. In the end, synergy and complementarity are the prime benefits. Further research must prioritize addressing feedback loops in models of urban shrinkage (SD) and of agent behavior (ABM).

Second, the inclusion of new social science knowledge of the demographic, socio-economic, housing, and governance aspects of urban shrinkage enables extensive and detailed information for modeling a widespread but scientifically neglected urban phenomenon. Although our approach is not as of yet participatory (although it can be further developed in this manner), the study already benefits from the interdisciplinary collaboration of modelers and social scientists from the very beginning of the research process. We believe that modelers and social scientists can learn from one another as they integrate different working approaches and disciplinary knowledge. For example, social scientists learn about modeling “their” issues insofar as we can translate complex social processes into clear modeling rules. Modelers learn that modeling a complex urban phenomenon such as shrinkage requires additional empirical and agent- and household-related knowledge to simulate and explain the process.

Using the case study of Leipzig, we demonstrated the specifics of shrinkage by using the following indicators: population decline, change in household structure due to demand side-friendly housing costs, proximity of growing and declining neighborhoods, decline in land-use density through the expansion of brownfields and emergence of unintended green spaces, and the concomitant new consumption of land.

Leipzig represents a meaningful example of a shrinking city because expertise from other shrinking cities across Europe show that many of the processes we claimed to be specific to Leipzig’s land-use change also apply to those cities, e.g., Liverpool (UK), cities of the Upper Silesian conurbation and Łódź (Poland), Ostrava (Czech Republic), Genoa (Italy). Leipzig also shows that there are opposing land-use developments in shrinking cities on different spatial levels (e.g., underuse of land vs. new land consumption, spreading perforation). This opposing land-use in shrinking cities leads to new debates over assessing long-term sustainability, an issue that demands collaborative work by modelers and social scientists in the future, as well as assessing the practical applicability of related findings in urban planning. In this paper, we presented an approach that uses stakeholder knowledge but is not yet consultative.

Further research should pay more attention to discover both the problems and benefits of shrinkage in term of land use, sustainable resource use and quality of life. Concerning simulation and modeling, there is a need for a simpler application of the modeling approach. Finally, the benefits of this approach for scientists, who are not experts in modeling, and decision-makers in urban planning have to be more obvious.

Acknowledgements

We would like to thank TobiaLakes for her comments on an earlier version of this manuscript and three anonymous reviewers for their reviews and invaluable comments, which profoundly helped to improve the quality of the manuscript. We also thank Bradley Schmidt for polishing the language. The EU 6 FP IP PLUREL (contract no. 036921) and the EU 7 FP project SHRINK SMART (contract no. 225193) financially supported the work.

References

- Abraham, J.E., 1998. A Review of the MEPLAN Modeling Framework from a Perspective of Urban Economics. Department of Civil Engineering Research Report No.CE98-2, University of Calgary.
- Agarwal, C., Green, G., Grove, M., Evans, T., Schweik, C., 2002. A Review and Assessment of Land-Use Change Models: Dynamics of Space, Time, and Human Choice Report of United States Department of Agriculture, Forest Service. General Technical Report NE-297. http://nrs.fs.fed.us/pubs/gtr/gtr_ne297.pdf.
- Amin, A., Thrift, N., 1994. Globalization, Institutions and Regional Development in Europe. Oxford.
- Axhausen, K., 2006. New model concepts for simulating traffic demand: developments, state of the art, perspectives. In: Proceedings of the 7th Aachener Colloquium on Integrated Microsimulation of Spatial and Transport Development, pp. 149–163. Theory, Concepts, Models, Practice.
- Banzhaf, E., Kindler, A., Haase, D., 2007. Monitoring, mapping and modeling urban decline: a multi-scale approach for Leipzig. *EARSeL eProceedings* 6 (2), 101–114.
- Barredo, J.I., Kasanko, M., McCormick, N., Lavalle, C., 2003. Modeling dynamic spatial processes: simulation of urban future scenarios through cellular automata. *Landscape and Urban Planning* 64 (3), 145–160.
- Batty, M., Xie, Y., 1994. From cells to cities. *Environment and Planning B* 21 (Supplement), 31–48.
- Batty, M., Xie, Y., Sun, Z., 1999. Modeling urban dynamics through GIS-based cellular automata. *Computers, Environment and Urban Systems* 23 (3), 205–233.
- Beauregard, R.A., 2009. Urban population loss in historical perspective: United States, 1820–2000. *Environment and Planning A* 41 (3), 514–528.
- Beckmann, K., 2006. Mikro-Simulation von Raum- und Verkehrsentwicklung – Stand der Kunst und Perspektiven zwischen Forschung, Entwicklung und Praxis (microsimulation of spatially and transport development – state of the art and perspectives between research, development and practice). In: Proceedings of the 7th Aachener Colloquium “Integrierte Mikro-Simulation von Raum- und Verkehrsentwicklung”, pp. 1–31. Theorie, Konzepte, Modelle, Praxis. Integrated microsimulation of spatial and transport development. Theory.
- Berling-Wolff, S., Wu, J., 2004. Modeling urban landscape dynamics: a review. *Ecological Research* 19 (1), 119–129.
- Bernt, M., 2009. Partnerships for demolition: the governance of urban renewal in East Germany's shrinking cities. *International Journal of Urban and Regional Research* 33 (3), 754–769.
- Blanco, H., Alberti, M., Forsyth, A., Krizek, K.J., Rodríguez, D.A., Talen, E., Ellis, C., 2009. Hot, congested, crowded and diverse: emerging research agendas in planning. *Progress in Planning* 71 (4), 153–205.
- Bundesministerium für Verkehr, Bau und Stadtentwicklung (BMVBS), 2010. Reurbanisierung der Innenstadt. Online-Publication, 19/2010.
- Bonabeau, E., 2002. Agent-based modeling: methods and techniques for simulating human systems. *PNAS* 99, 7280–7287.
- Cheng, J., Masser, I., 2003. Urban growth pattern modeling: a case study of WuhanCity, PR China. *Landscape and Urban Planning* 62, 199–217.
- Clarke, K., Gaydos, L., 1998. Loose-coupling a cellular automaton model and GIS: longterm urban growth prediction for San Francisco and Washington/Baltimore. *International Journal of Geographical Information Science* 12, 699–714.
- Costanza, R., 2003. A vision of the future of science: reintegrating the study of humans and the rest of nature. *Futures* 35, 651–671.
- Couch, C., Karecha, J., Nuissl, H., Rink, D., 2005. Decline and sprawl: an evolving type of urban development – observed in Liverpool and Leipzig. *European Planning Studies* 13 (1), 117–136.
- Couch, C., Cocks, M., Rink, D., Haase, A., Bernt, M., Großmann, K. Governance of shrinkage within a European context. Comparative analysis of cross-cutting themes (WP5 D11), EU 7FP project Shrink Smart – Governance of shrinkage within a European context (No. 225193), Leipzig, Helmholtz Centre for Environmental Research – UFZ, unpublished typescript, 11 pp.
- Couclelis, H., 1985. Cellular worlds: a framework for modeling micro - macro dynamics. *Environment and Planning A* 17 (5), 585–596.
- Couclelis, H., 1997. From cellular automata to urban models: new principles for model development and implementation. *Environment and Planning B* 24 (2), 165–174.
- De la Barra, T., 1989. Integrated Land Use and Transport Modeling, vol. 1. Cambridge University Press, Cambridge. Debate Initial 18, 14–21.
- Delden, H., Escudero, J.C., Uljee, I., Engelen, G., 2005. METRONAMICA: a Dynamic Spatial Land Use Model Applied to Vitoria-Gasteiz. Virtual Seminar of the MILES Project. Centro de Estudios Ambientales, Vitoria-Gasteiz.
- Delden, H., Hagen, A., Luján, P., Shi, Y.-e., van Vliet, J., 2008. Assessment and Scenarios of Land Use Change in Europe. Maastricht, The Netherlands.
- Dhawan, R., 2006. System Dynamics and Its Impact on Managerial Decision Making. University of Sydney (Hrsg.), Sydney.
- Doehler, M., Rink, D., 1996. Stadtentwicklung in Leipzig: Zwischen Verfall und Deindustrialisierung, Sanierung und tertiären Großprojekten. In: Häußermann, H., Neef, R. (Eds.), *Stadtentwicklung in Ostdeutschland: Soziale und räumliche Tendenzen*. Westdeutscher Verlag, Opladen, pp. 263–286.
- EPA (United States Environmental Protection Agency), 2000. Projecting Land-Use Change. A Summary of Models for Assessing the Effects of Community Growth and Change on Land-Use Patterns EPA-Report No. EPA/600/R-00/098. <http://faculty.washington.edu/pwaddell/Models/REPORTfinal2.pdf>. 17–136.
- Eppink, F., van den Bergh, J., Rietveld, P., 2004. Modeling biodiversity and land use: urban growth, agriculture and nature in a wetland area. *Ecological Economics* 51 (3–4), 201–216.
- Epstein, J.M., 1999. Agent-based computational models and generative social science. *Complexity* 4, 41–60.
- Fang, S., Gertner, G.Z., Sun, Z., Anderson, A., 2005. The impact of interactions in spatial simulation of the dynamics of urban sprawl. *Landscape and Urban Planning* 73, 294–306.
- Fontaine, C.M., Rounsevell, M.D.A., 2009. An agent-based approach to model future residential pressure on a regional landscape. *Landscape Ecology*.
- Fritsche, M., Langner, M., Köhler, H., Ruckes, A., Schüller, D., Zakirova, B., Appel, K., Contardo-Jara, V., Diermayer, E., Hofmann, M., Kulemeyer, C., Meffert, P., Westermann, J., 2007. Shrinking cities – a new challenge for research in urban ecology. In: Langner, M., Endlicher, W. (Eds.), *Shrinking Cities: Effects on Urban Ecology and Challenges for Urban Development*. Peter Lang, Frankfurt am Main, pp. 105–116.
- Garreau, J., 1991. *Edge City: Life on the New Frontier* (New York).
- Geertman, S., Stillwell, J., 2004. Planning support systems: an inventory of current practice. *Computers, Environment and Urban Systems* 28, 291–310.
- Geurs, K., van Wee, B., 2004. Land-use/transport interaction models as tools for sustainability impact assessment of transport investments: review and research perspectives. *European Journal of Transport and Infrastructure Research* 4 (3), 333–355.
- Großmann, K., 2007. *Schrumpfung zwischen Tabu und Thematisierung*. Berliner.
- Großmann, K., Haase, A., Rink, D., Steinführer, A., 2008. Urban shrinkage in East central Europe? Benefits and limits of a cross-National transfer of research approaches. In: Nowak, M., Nowosielski, M. (Eds.), *Declining Cities/Developing Cities: Polish and German Perspectives*. Instytut Zachodni, Poznań, pp. 77–99.
- Haase, D., Schwarz, N., 2009. Simulation models on human-nature interactions in urban landscapes – a review including system dynamics, cellular automata and agent-based approaches. *Living Reviews in Landscape Research* 3, 2.
- Haase, D., Seppelt, R., Haase, A., 2007. Land use impacts of demographic change – lessons from eastern German urban regions. In: Petrosillo, I., Müller, F., Jones, K.B., Zurlini, G., Krauze, K., Victorov, S., Li, B.-L., Kepner, W.G. (Eds.), *Use of Landscape Sciences for the Assessment of Environmental Security*. Springer, Dordrecht, pp. 329–344.
- Haase, D., Lautenbach, S., Seppelt, R., 2010. Applying social science concepts: modeling and simulating residential mobility in a shrinking city. *Environmental Modelling and Software* 25, 1225–1240.
- Haghani, A., Lee, S., Byun, J., 2003a. A system dynamics approach to land use/transportation system performance modeling. Part I: methodology. *Journal of Advanced Transportation* 37 (1), 1–41.
- Haghani, A., Lee, S., Byun, J., 2003b. A system dynamics approach to land use/transportation system performance modeling. Part II: application. *Journal of Advanced Transportation* 37 (1), 43–82.
- Han, J., Hayashi, Y., Cao, X., Imura, H., 2009. Application of an integrated system dynamics and cellular automata model for urban growth assessment: a case study of Shanghai, China. *Landscape and Urban Planning* 91, 133–141.
- Harvey, D., 2006. *Spaces of Global Capitalism: Towards a Theory of Uneven Geographical Development* (London).
- He, C., Okada, N., Zahng, Q., Shi, P., Zahng, J., 2006. Modeling urban expansion scenarios by coupling cellular automata model and system dynamic model in Beijing, China. *Applied Geography* 25, 323–345.
- Hunt, J.D., Kriger, D.S., Miller, E.J., 2005. Current operational urban land-use-transport modeling frameworks: a review. *Transport Reviews* 25 (3), 329–376.
- Itami, R.M., 1994. Simulating spatial dynamics: cellular automata theory. *Landscape and Urban Planning* 30 (1–2), 27–47.
- Jessen, J., 2006. Urban renewal – a look back to the future. The importance of models in renewing urban planning. *German Journal of Urban Studies* 45 (1), 1–17.
- Kabisch, S., 2007. Shrinking cities in Europe – reshaping living conditions in post-communist cities. experiences from eastern Germany. In: Komar, B., Kucharczyk-Brus, B. (Eds.), *Housing and Environmental Conditions in Post-Communist Countries*, Gliwice, pp. 175–192.
- Kabisch, N., Haase, D., 2009. Diversifying European agglomerations: evidence of urban population trends for the 21st century. *Population, Space and Place* 17, 236–253.
- Kabisch, S., Haase, A., Haase, D., 2006. Beyond growth – urban development in shrinking cities as a challenge for modeling approaches. In: Voinov, A., Jakeman, A., Rizzoli, A. (Eds.), *Proceedings of the IEMSS Third Biennial Meeting: "Summit on Environmental Modeling and Software"*. International Environmental Modeling and Software Society, Burlington, USA, July 2006. CD ROM. Internet: <http://www.iemss.org/iemss2006/sessions/all.html>, ISBN 1-4243-0852-6 978-1-4243-0852-1.
- Kabisch, S., Steinführer, A., Haase, A., Großmann, K., Peter, A., Maas, A., 2008. Demographic Change and Its Impact on Housing (Final report for the EURO-CITIES network, Brussels and Leipzig).

- Kabisch, N., Haase, D., Haase, A., 2009. Evolving reurbanisation? Spatio-temporal dynamics exemplified at the eastern German city of Leipzig. *Urban Studies* 47 (5), 967–990.
- Kasanko, M., Barredo, J.I., Lavalle, C., McCormick, N., Demicheli, L., Sagris, V., Brezger, A., 2006. Are European Cities becoming dispersed? *Landscape and Urban Planning* 77 (1–2), 111–130.
- Kazepov, Y., 2005. Cities of Europe. Changing Contexts, Local Arrangements, and the Challenge to Urban Cohesion, pp. 43–63. Blackwell Publishing Ltd, UK.
- Lagabrielle, E., Botta, A., Daré, W., David, D., Aubert, S., Fabricius, C., 2010. Modelling with stakeholders to integrate biodiversity into land-use planning – Lessons learned in Réunion Island (Western Indian Ocean). *Environmental Modelling and Software* 25 (11), 1413–1427.
- Lauf, S., Haase, D., Kleinschmit, B., Hostert, P., Lakes, T., 2012a. Uncovering land use dynamics driven by human decision-making. A combined model approach using cellular automata and system dynamics. *Environmental Modelling and Software* 27–28, 71–82. doi:10.1016/j.envsoft.2011.09.005.
- Lauf, S., Haase, D., Seppelt, R., Schwarz, N., 2012b. Simulating demography and housing demand in an urban region under scenarios of growth and shrinkage. *Environment and Planning B* 39.
- Le, Q.B., Seidl, R., Scholz, R.W., 2012. Feedback loops and types of adaptation in the modelling of land-use decisions in an agent-based simulation. *Environmental Modelling and Software* 27–28, 83–96.
- Lever, W.F., 1993. Reurbanisation – The policy implications. *Urban Studies* 30, 267–284.
- Li, X., Liu, X., 2007. Defining agents' behaviors to simulate complex residential development using multicriteria evaluation. *Journal of Environmental Management* 85, 1063–1075.
- Ligtenberg, A., Bregt, A.K., van Lammeren, R., 2008. Multi-actor-based land use modeling: spatial planning using agents. *Landscape and Urban Planning* 56, 21–33.
- Lorance Rall, E.D., Haase, D., 2011. Creative intervention in a dynamic city: a sustainability assessment of an interim use strategy for brownfields in Leipzig, Germany. *Landscape and Urban Planning* 100, 189–201.
- Lütke-Daldrup, E., 2003. Die perforierte Stadt – neue Räume im Leipziger Osten. *Informationen zur Raumentwicklung* 1/2, 55–67.
- Matthews, R.B., Gilbert, N.G., Roach, A., Polhill, J.G., Gotts, N.M., 2007. Agent-based land-use models: a review of applications. *Landscape Ecology* 22, 1447–1459.
- Moss, T., 2008. 'Cold spots' of urban infrastructure: 'Shrinking' processes in eastern Germany and the modern infrastructural ideal. *International Journal of Urban and Regional Research* 32 (2), 436–451.
- Müller, B., 2004. Demographic change and its consequences for cities: introduction and overview. *German Journal of Urban Studies* 44. http://www.difu.de/publikationen/dfk/en/03_1/welcome.shtml.
- Municipality of Leipzig, 2006. Monitoringbericht 2005. Municipality of Leipzig.
- Noordwijk, M., Lusiana, B., Villamor, G., Purnomo, H., Dewi, S., 2011. Feedback loops added to four conceptual models linking land change with driving forces and actors. *Ecology and Society* 16 (1) [online] URL: <http://www.ecologyandsociety.org/vol16/iss1/resp1/>.
- Nuissl, H., Rink, D., 2005. The 'production' of urban sprawl in eastern Germany as a phenomenon of post-socialist transformation. *Cities* 22, 123–134.
- Nuissl, H., Haase, D., Wittmer, H., Lanzendorf, M., 2008. Impact assessment of land use transition in urban areas – an integrated approach from an environmental perspective. *Land Use Policy* 26, 414–424.
- Oswalt, P., Rieniets, T. (Eds.), 2006. *Atlas of Shrinking Cities*. Hatje, Ostfildern.
- Oxley, T., McIntosh, B.S., Winder, N., Mulligan, M., Engelen, G., 2004. Integrated modeling and decision-support tools: a Mediterranean example. *Environmental Modelling and Software* 19, 999–1010.
- Parker, D.C., Manson, S.M., Janssen, M.A., Hoffmann, M.J., Deadman, P., 2003. Multi-agent systems for the simulation of land use and land cover change: a review. *Annals of the Association of American Geographers* 93 (2), 314–337.
- Petrov, L., Haase, D., Lavalle, C., 2009. MOLAND Model results for the Leipzig region. *PLUREL Newsletter* 5, 5.
- Ravetz, J., 2000. *City Region 2020. Integrated Planning for a Sustainable Environment*. Earthscan, London.
- Rieniets, T., 2006. Urban shrinkage. In: Oswalt, P., Rieniets, T. (Eds.), *Atlas of Shrinking Cities*. Hatje, Ostfildern, p. 30.
- Rieniets, T., 2009. Shrinking cities: causes and effects of urban population losses in the twentieth century. *Nature and Culture* 4 (3), 231–254.
- Rink, D., 2009. Wilderness: the nature of urban shrinkage? The debate on urban restructuring and restoration in eastern Germany. *Nature and Culture* 3 (1), 275–292.
- Rink, D., Haase, A., Bernt, M., 2009. Specification of Working Model, WP1 Research Report for the EU 7FP Project Shrink Smart – Governance of Shrinkage Within a European Context (No. 225193). Helmholtz Centre for Environmental Research – UFZ, Leipzig. www.shrinksmart.ufz.de/documents/WP1.
- Sanders, P., Sanders, F., 2004. Spatial Urban Dynamics. A Vision on the Future of Urban Dynamics: Forrester Revisited. Paper presented at the 2004 International System Dynamics Conference at Oxford, UK. http://www.systemdynamics.org/conferences/2004/SDS_2004/PAPERS/119SANDE.pdf.
- Sawyer, R.K., 2003. Artificial societies: multiagent systems and the micro-macro link in sociological theory. *Sociol Methods Res* 31, 325–363.
- Schaldach, R., Alcamo, J., Koch, J., Kölling, C., Lapola, D.M., Schüngel, J., Priess, J.A., 2011. An integrated approach to modelling land-use change on continental and global scales. *Environmental Modelling and Software* 26 (8), 1041–1051.
- Schnase, J.L., Cushing, J., Frame, M., Frondorf, A., Landis, E., Maier, D., Silberschatz, A., 2003. Information technology challenges of biodiversity and ecosystems informatics. *Information Systems* 28, 339–345.
- Schwarz, N., Haase, D., Seppelt, R., 2010. Omnipresent sprawl? A review of urban simulation models with respect to urban shrinkage. *Environment and Planning B* 37, 265–283.
- Schwarz, N., Kahlenberg, D., Haase, D., Seppelt, R. A generic framework for collaborative agent-based model development. *JASSS*, in press.
- Sterk, B., Van Ittersum, M.K., Leeuwis, C., 2011. How, when, and for what reasons does land use modelling contribute to societal problem solving? *Environmental Modelling and Software* 26 (3), 310–316.
- Sterman, J.D., 2002. All models are wrong. Reflections on becoming a system scientist. *System Dynamics Review* 18 (4), 501–531.
- Storper, M., 1995. The resurgence of regional economies, ten years later: the region as a nexus of untraded interdependencies. *European Urban and Regional Studies* 2, 191–221.
- Storper, M., Manville, M., 2006. Behaviour, preferences and cities: urban theory and urban resurgence. *Urban Studies* 43, 1247–1274.
- Sui, D., Zeng, H., 2001. Modeling the dynamics of landscape structure in Asia's emerging desakota regions: a case study in Shenzhen. *Landscape and Urban Planning* 53 (1), 37–52.
- Theobald, D.M., Gross, M.D., 1994. EML: a modeling environment for exploring landscape dynamics. *Computers, Environment and Urban Systems* 18 (3), 193–204.
- Timmermans, H., 2003. The Saga of Integrated Land Use-Transport Modeling: How Many More Dreams Before We Wake up? Paper Presented at the 2003 10th International Conference on Travel Behaviour Research, Lucerne, Switzerland. <http://www.ivt.baug.ethz.ch/allgemein/pdf/timmermans.pdf>.
- Turok, I., Mykhnenko, V., 2007. The trajectories of European cities, 1960–2005. *Cities* 24 (2), 165–182.
- Valbuena, D., Verburg, P.H., Bregt, A.K., 2008. A method to define a typology for agent-based analysis in regional land-use research. *Agric Ecosyst Environ* 128, 27–36.
- van den Berg, L., Drewett, R., Klaasen, L., 1982. *Urban Europe: a Study of Growth and Decline* (Oxford).
- Van Vliet, J., White, R., Dragicevic, S., 2009. Modeling urban growth using a variable grid cellular automaton. *Computers, Environment and Urban Systems* 33 (1), 35–43.
- Verburg, P.H., 2006. Simulating feedbacks in land use and land cover change models. *Landscape Ecology* 21, 1171–1183.
- Verburg, P., Schot, P., Dijst, M., Veldkamp, A., 2004. Land use change modeling: current practice and research priorities. *GeoJournal* 61 (4), 309–324.
- Waddell, P., 2002. UrbanSim: modeling urban development for land use, transportation and environmental planning. *Journal of the American Planning Association* 68 (3), 297–314.
- White, R., Engelen, G., 2000. High-resolution integrated modeling of the spatial dynamics of urban and regional systems. *Computers, Environment and Urban Systems* 24, 383–400.
- Wickramasuriy, R., Chisholm, L.A., Puotinen, M., Gill, N., Klepeis, P., 2011. An automated land subdivision tool for urban and regional planning: concepts, implementation and testing. *Environmental Modelling and Software* 26 (12), 1675–1684.