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Simulation Models on Human–Nature Interactions in Urban Landscapes: A Review Including Spatial Economics, System Dynamics, Cellular Automata and Agent-based Approaches

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Abstract

Urbanisation belongs to the most complex and dynamic processes of land use and landscape change. At present, we claim "the millennium of the cities," since more than half of the currently 6.6 billion world population is living in urban areas. Due to the huge impact of urban land consumption on environment and landscape, this paper provides a review of existing urban land use models. The review analyses non-spatially explicit economic and system dynamics models, spatially explicit cellular automata and agent-based model approaches by addressing the respective conceptual approach, model components and causal relationships, including feedbacks. Based upon the review, conclusions are drawn regarding the future development of urban landscape models, as well as on indispensable causal relationships and their representation when modelling urban systems.

Keywords: urban landscape, simulation models, land use change, review, system dynamics, cellular automata, agent-based model, feedback, causalities

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1 Introduction

1.1 Urbanisation of landscapes

Urbanisation is one of the most complex and dynamic processes of landscape change. Although only about 4% of the world's land area is urbanised and densly populated (Ramankutty *et al.*, 2006), we claim "the millennium of the cities," since more than half of the currently 6.6 billion world population is living in urban areas (United Nations, 2008, 2009; PRB, 2007; EEA, 2006; Kasanko *et al.*, 2006). Projections for the future show that urbanisation – in terms of an increasing share of population living in urban areas – is very likely to continue (Batty *et al.*, 2003; EEA, 2006; Lutz *et al.*, 2001). Urbanisation is not only a societal problem, but also an environmental one, because it contradicts a normative ideal of "a natural or un-spoiled landscape" in spatial planning (Nuissl *et al.*, 2008). In a multitude of studies it has been shown that land consumption is usually detrimental to the environment in different regards (e.g., Johnson, 2001; Antrop, 2004). Its impact reduces the ability of landscapes to fulfil human requirements and thus impairs ecosystem services and landscape functions in various ways (de Groot *et al.*, 2002; Millennium Ecosystem Assessment, 2005; Curran and de Sherbinin, 2004). Individual ecosystem services and quality of life aspects that are affected by urbanisation include the production of food, the regulation of energy and matter flows, water supply, the provision of biodiversity and of health and recreation, and the supply of green space and natural aesthetic values (Alberti, 1999). Suburbanisation and urban sprawl were the dominating land consumption processes in North America and Europe after WW II (Batty, 2008). Recently, high growth rates in developing countries have led to enormous environmental loads as discussed above (Heinrichs and Kabisch, 2006). As urban systems are very densely populated and their land use components highly interlinked (Liu *et al.*, 2007), developing views about their future is both a major concern in landscape research and a complex task. Modelling land use relationships helps to understand underlying drivers of land use change, to create future land use scenarios and assess possible environmental impacts (Lambin and Geist, 2006; Ravetz, 2000).

1.2 The "ideal" urban land use model

A variety of land use change models, particularly for urban landscapes, already exist, ranging from specific case studies to generic tools for a variety of urban regions. These models differ largely in terms of their structure, their representation of both space and human decisions, and their methodological implementation. Compared to land use change models in open landscapes, urban areas are shaped particularly by human activities, societal processes and human–nature interactions (Couclelis, 1997). In addition to implemented simulation models, a number of articles and book chapters elaborate on the "ideal" integrated model, theoretically necessary causal feedback loops etc. These "ideal" models shall serve as analytical frameworks to better understand the systems under study. Often, authors use frameworks like the DPSIR-framework (drivers, pressures, state, impact, responses) of the European Environment Agency (EEA) to conceptualise these conceptual models. According to Verburg, "the main drawback of using these analytical frameworks is the assumption of one-directional processes between driving factors and impacts" (Verburg, 2006, p. 1173), because in reality, it is difficult to differentiate between impacts and drivers in a system. Bürgi *et al.* (2004) distinguish five major types of driving forces: socioeconomic, political, technological, natural and cultural. Furthermore, they differentiate between primary, secondary and tertiary driving forces, as well as between intrinsic and extrinsic driving forces (Bürgi *et al.*, 2004). In their introduction to urban simulation, Waddell and Ulfarsson (2004) sketched urban markets and agents, choices and interactions in an "ideal" urban land use model. Timmermans (2006) criticizes that present urban models focus on functional chains like the following: demand causes allocation across space, which in turn causes traffic flows, based upon which a transportation model calculates travel times, which in turn explain residential choice. Timmermans votes to include other aspects of integration in urban land use models, such as task allocation within households, residential choice, job choice, vehicle ownership, scheduling of activities, competition and agglomeration of land uses and actors, co-evolutionary development of demographics, employment sectors, land use and activity profiles and a more thorough treatment of varying time horizons, including anticipatory and reactive behaviour. According to Miller *et al.* (2004), an integrated urban systems model with a focus on transport should include socio-demographic components (evolution of population), demographics (demographic change and migration into and out of a region), decision-making (location choices of households and firms), economic variables (labour market, import/export of goods and services), transportation (activity and travel patterns of population, goods and services, depending upon urban structure and economic interchanges, performance of road and transit systems) and respective effects on land use (evolution of the built environment) and environment (atmospheric emissions generated by transportation and industry; Miller *et al.*, 2004). Moreover, Hunt *et al.* (2005) stated eleven modelling axioms for such an "ideal urban land use model":

- Representation of an urban system should focus on those elements that interact with the transportation system.
- An urban system consists of physical elements, actors and processes.
- A transportation system is multimodal and involves both people and goods.
- Markets are the basic organising principle of an urban system.
- Flows of people, goods, information and money arise out of demand.
- Urban areas do not reach an equilibrium.
- System time must be explicitly dealt with.
- Feedback between short-term and long-term processes has to be integrated (e.g., travel and infrastructure).
- Some factors may be treated as exogenous for modelling purposes.
- Some activities arise in response to external demand.
- A very detailed level of representation for actors and processes is necessary.

1.3 Existing reviews on urban land use models

A variety of reviews including urban land use models already exist: Agarwal *et al.* (2002) as well as Schaldach and Priess (2008) review integrated land use models in general, also including models that deal with non-urban land uses such as forestry, pasture and agriculture. Axhausen (2006) specialises in models on transportation demand and traffic flows. Beckmann (2006) and Iacono *et al.* (2008) focus on interactions between urban land use and transportation. The authors predominantly discuss modelling approaches and does not give details regarding single models. Similar to this, Berling-Wolff and Wu (2004) provide an historical overview of modelling approaches and do not discuss single models. The U.S. EPA (2000) focuses on models of urban growth and sprawl but mainly includes U.S. American approaches and – because of its publication date – does not include recently published models. Geurs and van Wee (2004) and Hunt *et al.* (2005) focus on models which emphasize the interaction between urban land use and the transportation system. Furthermore, Timmermans (2006) gives a historical overview and describes a large number of models but does not give a comparative description of presently developed models. With his review on modelling the urban ecosystem, Alberti (2008) puts less emphasis on urban land use change, but rather focues on the environmental impacts and human-induced environmental stress of the urban system. The review utilises a range of evaluation criteria, of which feedback mechanisms, multiple actors and the inclusion of uncertainy are seen as the most challenging (Alberti, 2008). Finally, Verburg *et al.* (2004) sketch a few exemplary models, but their focus lies on discussing general modelling approaches and not on single causal feedbacks.

1.4 The purpose of this review

Set against the background summarised in Section 1.3, this review analyses economic models, system dynamics approaches, cellular automata and agent-based models developed for urban systems by systematically addressing a range of critieria such as the conceptual approach, model components and included variables. In doing so, it aims at giving an overview on the respective model structures. The main purpose of the review is to derive ideas for causal relationships within land use change in urban systems, with a special emphasis on integrating social and natural science dimensions. The innovative aspect of this review compared to existing reviews is the aim to explicitly analyse causalities and feedbacks in urban land use changes.

As Verburg (2006) points out, an integration of social and biophysical systems could be enhanced by including feedback mechanisms in land use models, e.g., the feedback between driving factors and effects of land use change (here understood as impacts), the feedback between local and regional processes, and the feedback between agents and spatial units (Verburg, 2006). "Less common in land use modelling is the simulation of feedbacks between impacts on socio-economic and environmental conditions and the driving factors of land use change" (Verburg, 2006, p. 1173). Therefore, the review presented here will include a glance at those feedbacks. Since urban land use models deal with spatial entities – that is, among others, the landscape itself – an important aspect of selecting modelling approaches for the review is spatial explicitness in terms of landscape property. In addition, urban landscapes are highly complex, as highlighted in several paragraphs of the introduction part of this paper; therefore, one should focus on comprehensive models that include different relationships, influences and dependencies along with their spatial representation. The paper is organised as follows. Section 2 sets up a set of evaluation criteria for conducting the model review, which follows in Section 3. Section 4 especially focuses on causalities and feedback loops of land use change, before coming to the paper's conclusions (Section 5).

2 Evaluating urban land use simulation models

Compared to natural or agricultural landscapes, urban systems are strongly influenced by both the social and the natural dimension. As mentioned in the introduction, urban landscapes are coupled with human–nature systems (Liu *et al.*, 2007), with many interlinkages between the human sphere – first and foremost demography and economy – land use and the environment. Figure 1 provides a very general but comprehensive overview on the major components of an urban landscape: the major driving force for change is the human sphere, which creates pressures on the state of the land use, which again will have effects on the environment, its natural resources and ecosystems.

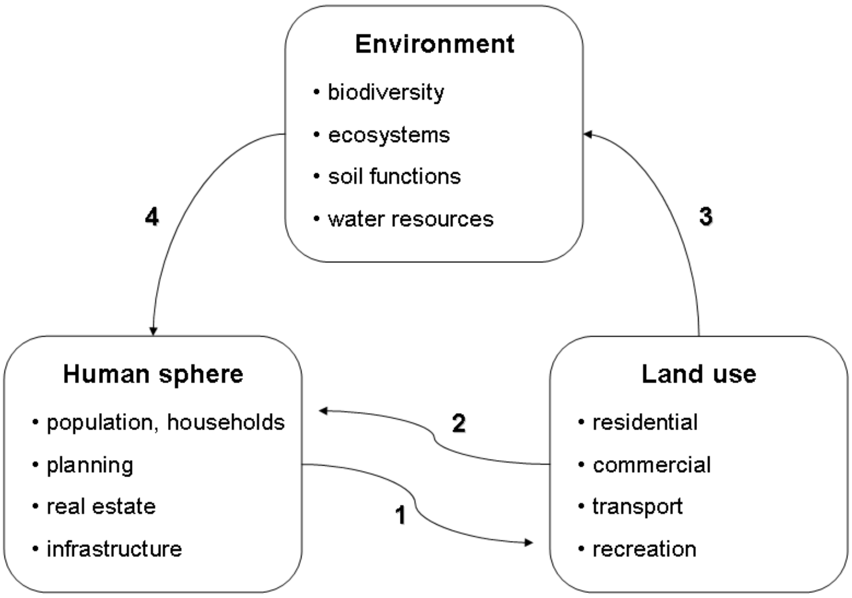


Figure 1: Main components (human sphere, land use, natural resources) and relationships (1 – 4) which describe human–nature interactions in urban regions: (1) Impact of human sphere on land use, (2) feedback of land use on human sphere, (3) impact of land use on environment (including ecosystems) and (4) feedback of environment on human sphere.

The human sphere characterises the socio-economic system of cities: it comprises variables such as population (development), households, spatial planning and governance, the real estate market, commercial activities and infrastructure, including transportation. Specifically, the human sphere includes human decision making and actions upon land use. The land use component itself comprehends all types of typical urban land uses such as residential, industrial, commercial, transport and recreation. The third component contains natural resources, such as ecosystems, biodiversity, soil functions and water resouces (cf. again Figure 1). We set up these feedback loops between the three dimensions/components of the urban system discussed above: (1) the impact of the human sphere on land use, (2) the feedback (= reverse to the impact function) of land use on the human sphere, (3) the impact of land use on the environment and (4) another feedback of the environment on the human sphere. All relationships are labelled in Figure 1, respectively. Furthermore, a short Section (4.4) deals with the scale-specific causal feedbacks between local and regional scale, insofar as they are covered by the models investigated. The evaluation of the feedback loops includes (1) the identification of a respective formal representation of the respective causalities in the model and (2) whether or not they have an impact on other model components again/vice versa. In order to structure the review and to give brief overviews of the models under review, we summarised the findings of the analysis of each of the models in Table 1, which provides comprehensive information about the main purpose and major components classified according to Figure 1.

3 Models under review

With respect to the model evaluation criteria mentioned in previous reviews and for the "ideal urban model" (Sections 1.2 and 1.3), we solely focus on causalities and feedback loops in the models under review, as we believe that alongside a good description of model components (human sphere, land use, environment), representation of the linkages between the components (= impacts and feedback loops) make up the comprehensiveness and the explanatory strength of the models. The models included in this review were selected in order to represent the most influential streams of urban land use change modelling. First, the review includes models well known within the community, such as those which are discussed in the related literature on urban land use change, e.g., by being referenced in other reviews. Second, system and land use approaches which are not discussed at great length in the literature were included, because system dynamics as a method forces modellers to think in a systemic way and easily allows for the inclusion of feedback mechanisms. For system-oriented, causality-driven models on at least one dimension of urban land-use change, a search on the ISI Web of Science was performed. This procedure led to a total of 19 models, which were also included in this review. These models are listed in the form of a comprehensive overview in Table 1. Details are given in the Annex 7.

Roughly four different modelling approaches can be distinguished. Two of the models under review belong to the class of spatial economics/econometric models (SE_1 and SE_2: Nijkamp *et al.*, 1993; Mankiw and Weil, 1989). These models mainly look at demography and household-driven demand-supply relations in urban regions, such as housing market developments. Seven models included in this review (SD_1 to SD_7: Forrester, 1969; Haghani *et al.*, 2003a,b; Eppink *et al.*, 2004; Sanders and Sanders, 2004; Onsted, 2002; Eskinasi and Rouwette, 2004; Raux, 2003) are system dynamics or causality-driven models (Table 1). System dynamics is an approach which models complex systems using stocks and flows and by explicitly including feedback loops in the model (Sterman, 2000). System dynamics models are – in their standard application – not spatially explicit. Rather, the structure of combining stocks, flows and feedback mechanisms leads to a set of differential equations. The outcome of these equations can be simulated, given values for parameters and initial conditions. The classical approach to modelling urban systems using system dynamics is Forrester's book on "Urban Dynamics" (Forrester, 1969): He linked the three subsystems "business," "housing" and "population" to describe and model urban systems in general, subsequently differentiating each of the three subsystems in very detailed sub-models. Five models included in this review (CA_1 to CA_5: Verburg and Overmars, 2007; Landis and Zhang, 1998a,b; Landis *et al.*, 1998; Engelen *et al.*, 2007; Dietzel and Clarke, 2007) use cellular automata as the main modelling technique (Table 1). A cellular automaton consists of an n-dimensional grid of cells. Each cell has a finite number of states. Cells change their state simultaneously according to the same rules coded in the model, and the state of a cell in time t solely depends on the state of neighbouring cells in t_{-1} (cf. Clarke *et al.*, 1997; Landis and Zhang, 1998a,b; Silva and Clarke, 2002). Land use change models use cellular automata with 2-dimensional grids which represent the majority of land use. Each cell symbolises a patch of land, and states of cells are the land use options. Five models in this review (ABM_1 to ABM_5: Strauch *et al.*, 2003; Salvini and Miller, 2005; Ettema *et al.*, 2007; Loibl *et al.*, 2007; Waddell *et al.*, 2003) use agent-based approaches as the main modelling technique (Table 1). Agent-based models consist of autonomous individuals (agents) who perceive their environment and interact with one another (Parker *et al.*, 2003). Applications of agent-based modelling in land use change are usually spatially explicit, and agents represent, for example, households relocating their homes or individuals using transport systems, but also governmental and other institutional bodies.

Table 1: Overview of main purposes and components (according to Figure 1) investigated in reviewed models.

Model	Main purpose	Components	Reference
Spatial Economics / Econometric models			
SE_1	Modelling household life cycles and their impact on residential relocation behaviour and the urban housing market for a European capital city.	Human sphere (population, migration, household, transportation, housing market, prices, dwellings, vacancies)	Nijkamp *et al.* (1993)
SE_2	Simulation of demographic changes (baby boom and baby bust) and its influences on the housing market in the U.S.	Human sphere (population, migration, household, housing market, prices, dwellings, vacancies)	Mankiw and Weil (1989)
System Dynamics			
SD_1	Modelling urban system in general, explicitly including "urban decline." Examples: focus on a specific topic, e.g., rapid population growth, demolition, et cetera and therefore need specific models.	Human sphere (business, housing, population)	Forrester (1969); Alfeld (1995)
SD_2	Integrated land-use and transportation model for estimating scenarios regarding transport policies	Human sphere (population, migration, household, job growth, employment and commercial land development, housing development, travel demand, congestion)	Haghani *et al.* (2003a,b)
SD_3	Assessing the impact of urban sprawl on wetland biodiversity and social welfare	Human sphere (population) Land use (agricultural land, wetlands) Environment (wetlands, nature protection)	Eppink *et al.* (2004)
SD_4	Redefining the model of urban dynamics by Forrester (1969), including: 1. spatial dimension (16 squares) and 2. disaggregation: different types of housing, industry, and people in zones	Human sphere (population, housing availability, houses, land availability, business structures, and job availability, labour market and housing market)	Sanders and Sanders (2004)
SD_5	Simulation model to provide scenarios for future land use in Santa Barbara, e.g., with restrictions to urban growth	Human sphere (housing, population, business) Land use Quality of life	Onsted (2002)
SD_6	Assessing the impact of future policy interventions on the social housing market (specific: rate of building new dwellings)	Human sphere (commercial housing stock, social housing stock, waiting families, supply of available social houses; migration, demolition, construction)	Eskinasi and Rouwette (2004)

Table 1 – *Continued*

Model	**Main purpose**	**Components**	**Reference**
SD_7	Simulating medium- and long-term effects of urban transportation policies with reference to sustainable travel	Human sphere (urbanisation, internal travel demand, car ownership, external travel demand, transportation, socio-economic evaluation) Environment (environmental appraisals)	Raux (2003)
Cellular Automata			
CA_1	Tool for understanding land-use patterns, possible future scenarios for given demand	Human sphere (demand rules) Land use (suitability rules)	Verburg and Overmars (2007)
CA_2	Simulating urban growth, scenarios for future development	Human sphere (population, household, jobs, employment) Land use (single-family residential, multi-family residential, commercial, industrial, transportation, public) Environment (undeveloped land)	Landis and Zhang (1998a,b)
CA_3	Development of policy scenarios of urban growth, impact on habitat change/biodiversity	Human sphere (urban growth, policy simulation and evaluation) Environment (habitat change and habitat fragmentation)	Landis *et al.* (1998)
CA_4	Monitoring developments of urban areas and identifyng trends at the European level, focus is on growth scenarios	Human sphere (population, economy, planning, accessibility via transportation network) Land use (land use functions)	Engelen *et al.* (2007)
CA_5	Modelling urban growth, scenarios for future development of an urban region	Land use (urban or non urban, roads, different land use types) Environment (topography)	Silva and Clarke (2002); Dietzel and Clarke (2007)
Agent-Based Models			
ABM_1	Dynamic simulation model with a focus on urban traffic flows, including activity behaviour, changes in land use, and effects on environment	Human sphere (activity patterns and travel demand, traffic flows, goods transport, accessibility of locations, location decisions of households, firms, developers) Land use (moving households, location of firms, investment of developers, new industrial area) Environment (clean air, traffic noise)	Strauch *et al.* (2003); Moeckel *et al.* (2006)
ABM_2	Evolution of an entire urban region with emphasis on transportation	Human sphere (location choice, activity schedule, activity patterns, automobile ownership, travel demand) Land use (land development, transportation network)	Salvini and Miller (2005); Miller *et al.* (2004)

Table 1 – *Continued*

Model	**Main purpose**	**Components**	**Reference**
ABM_3	Predicting urbanisation with behavioural agents	Human sphere (demographic change, decisions of individuals)	Ettema *et al.* (2007)
ABM_4	Development of built-up area in peri-urban region, driven by households and entrepreneurs; urban growth with different growth rates	Human sphere (households, jobs, numbers of people, households and workplaces at the start of the year, average travel time to district centres and capital city) Land use (urban land, open space, forest area)	Loibl *et al.* (2007)
ABM_5	Link between transport and land use; impact of different planning strategies	Human sphere (population, households, employment, travel demand, accessibility, mobility, real estate, land price) Land use	Waddell (2006); Waddell *et al.* (2003)

4 Representation of urban landscapes

One of the major aspects which urban land use models have to represent are causalities and feedbacks related to human–nature interactions. The main components representing an urban system, according to the models under review, are summarised in Tables 1 and 2. Spatial Economic models are labelled SE, Cellular Automata CA, System Dynamics Models SD, and Agent-Based models ABM.

Table 2: Main components of urban systems – do the models under review include them?

	Human sphere	**Land use**	**Environment**
(Spatial) Economic models			
SE_1	x	x	
SE_2	x	x	
System dynamics			
SD_1	x	x	x
SD_2	x	x	
SD_3		x	x
SD_4	x	x	
SD_5	x		x
SD_6	x	x	
SD_7		x	
Cellular automata			
CA_1	x		
CA_2	x	x	
CA_3	x	x	x
CA_4	x		x
CA_5			x
Agent-based models			
ABM_1	x	x	
ABM_2	x	x	x
ABM_3	x	x	
ABM_4	x	x	
ABM_5	x	x	

Structural relationships between model components and variables are found to be very different in the models (Figures 2 and 3). This is due to the fact that levels of rules for land use change vary largely, depending on the modelling technique used, i.e., (spatial) economics, system dynamics, cellular automata or agent behaviour (Table 2).

The first model group, (spatial) economic or econometric models, sets up a formalised relationship between population and market; in our case these compounds are the housing market and residential land use. Spatial economics models can be dynamic (when model parameters are treated endogeneously) or quasi dynamic (if model parameters are fixed or an exogeneous input during the model runtime). Generally, such models define a demand based on a population/household/cohort, etc., number, but only a limited feedback is generated from the net supply to the original driver (in our case: population). Cellular automata derive probabilities of land use change for a certain cell out of historical land use data (Engelen *et al.*, 2007; Barredo *et al.*, 2003) or by using try-and-error “calibrations” (Hansen, 2007). Therefore, they do not explicitly deal with causal relationships between urban drivers and land use states. Driving forces of the human sphere, such as population dynamics, residential mobility or price elasticise of the real estate market, can be included as scenario assumptions in some of the models in order to define the magnitude of urban sprawl (e.g., CA_2, CA_4). Nevertheless, the decision about which cells change their land use in which way is based upon historical land use change patterns. In contrast, landscape properties like topography, hydrography or morphology are reflected in most of the cellular models (CA_1; CA_3 – CA_5; Table 2). Using a different approach, agent-based models include individual and institutional actors to explicitly simulate processes of land use conversion. The main actors in these models are individuals or households, which choose their residential location according to their preferences, local industries and businesses which choose their location and employ local people, and institutions, which steer land use development by planning, permitting or restricting land use change, et cetera. Therefore, these models explicitly name the decision-making processes relevant for urban land use changes (ABM_1 – ABM_5). System dynamics models lie between these two "extremes": They include the processes, but in an aggregate way without incorporating single actors and their individual goals (Table 2).

In the following, the processes captured in the simulation models are analysed with respect to the feedbacks mentioned in Section 2.

4.1 Spidergrams

For comparison purposes, we set up an assessment matrix, in which the degree of fulfilment of the four relationships (cf. again Figure 1) is assigned to each of the models under review. We used a metric scale from 0 to 2: If the criterion is fulfilled, then the "mark" 2 is given; if only parts of the criterion are fulfilled – e.g., the processes implemented by rudimentary or very simple – the "mark" 1 is given; and if the criterion is not at all fulfilled or not included in the model, the "mark" 0 is given. The results of the model assessment are given in forms of simple multicriteria spidergrams which compare the three types of models (SE, SD, CA and ABM; Figure 2) for all criteria and, in a second range of graphs, all models for each single criterion (Figure 3).

4.2 Relationships between human sphere and land use

Most of the models under review represent the impact of human sphere on land use. Table 1 provides an overview of the model components. Except for three model approaches, each model covers population dynamics and housing or built-up land, which belong to the major variables either for human sphere or land use. The spidergram in Figure 2 clearly shows that causal relationships between human drivers are better captured than the reverse feedback from urban land development to the human drivers. Agent-based approaches mainly cover both loops, since land use variables belong to the neighbourhood of the agents and thus directly influence decision making. In comparison, spatial economics and system dynamics models comprehensively cover loops of type 1 "human sphere to land use," but mostly neglect effects of changing urban land use on population dynamics or economic development. Cellular automata do include some feedbacks from the effects of land use changes on the human sphere.

4.3 Impact of land use on environment

Only very few simulation models close the loop between driving forces and environmental impacts. Cellular automata perform better in capturing the effects of relatively simple rule-based or neighbourhood-statistic driven land use changes on the environment. Since they are often spatially explicit, landscapes can be more easily represented (cf. again Figure 2). For example, in CA_3, the impact of urbanisation on biodiversity is assessed, but no feedback to driving forces is taken into account. In SD_7, the impact of transport on the environment is integrated, but it is not

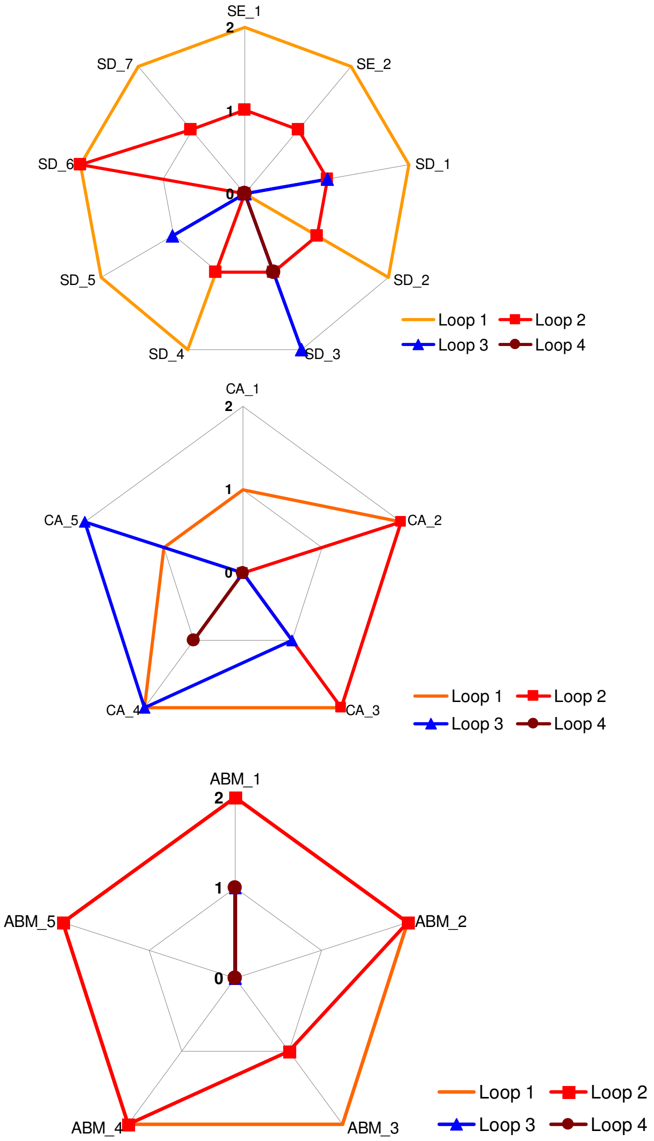
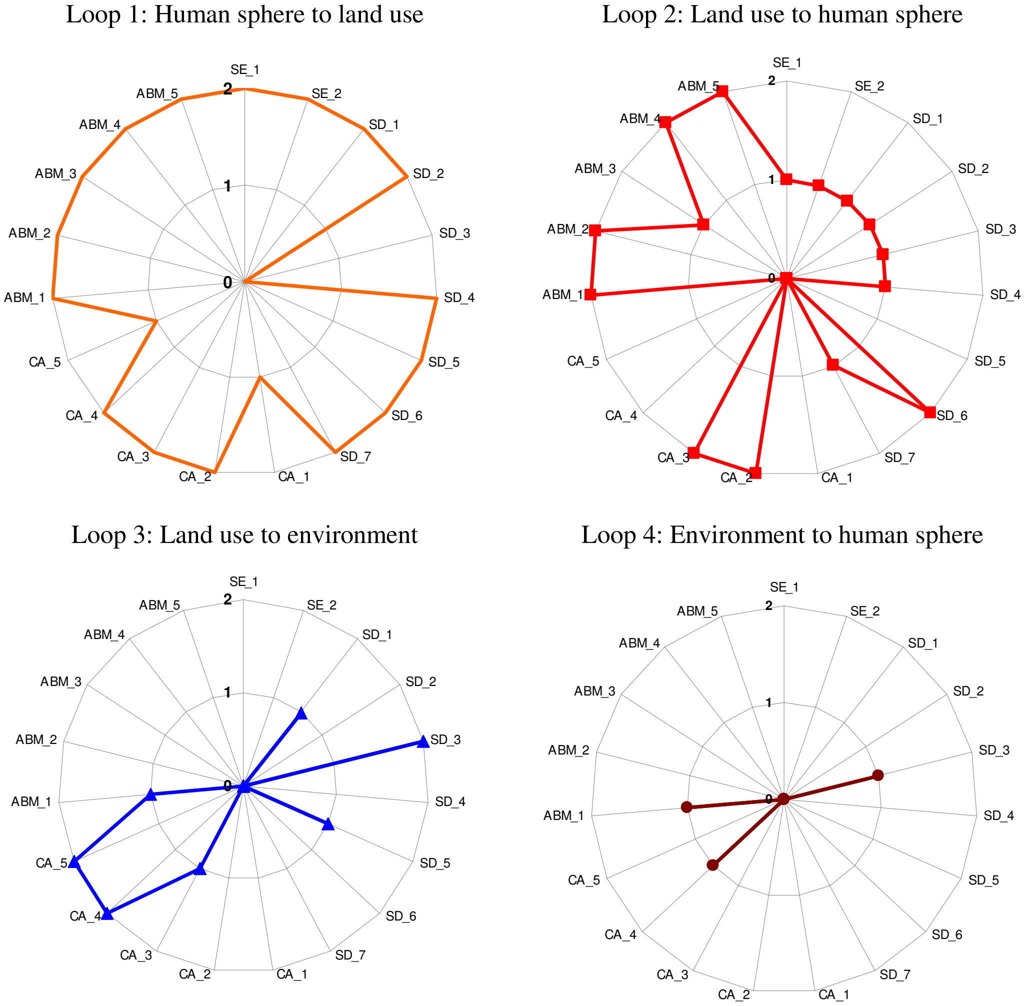


Figure 2: Spidergrams showing how far the reviewed models (according to their model type) incorporate the four relationships set up for model evaluation.



Loop 1: Human sphere to land use

Loop 2: Land use to human sphere

Loop 3: Land use to environment

Loop 4: Environment to human sphere

Figure 3: Spidergrams showing to which extent all reviewed models include the four loops.

clear from the available literature if there is a feedback to driving forces (travel and transportation flows). The two economics models under review (SE_1 and SE_2) lack spatial explicitness to be able to capture a more comprehensive land use relation or feedback.

4.4 Feedback from environment to human sphere

Feedbacks from environmental impacts back to the driving forces that cause urban land use change are mostly realised through changing attractiveness of grid cells or regions for household residential location choices. Those were found in ABM_4 (open space, forest area), ABM_1 (traffic noise, air quality), CA_4 (quality and availability of space for activities), and SD_5 (traffic volume produces air pollution and thus affects human quality of life). In SD_3, the decrease of wetland area (and its negative impact on biodiversity) directly influences decisions to buy land for nature protection instead of further urbanisation. These relationships are the only ones that close the loop from households/individuals as drivers of land use change to environmental impacts and back to the original decision algorithm.

4.5 Feedbacks between local and regional scale

Feedbacks between the local and regional scale can be realised in a variety of ways: first, migration of population within single districts can have an influence on the attractiveness of the districts and therefore influence the housing market in the region, which in turn affects migration. Second, planning and governance on the regional scale can influence local land use changes, which in turn can impact regional planning. In several of the models, the housing market (or price development) is captured implicitly or explicitly. For example, in the spatial economics models SE_1 and SE_2, as well as in the system dynamics models SD_2 and SD_4, the housing market and housing development are explicitly included: In the two former cases in the form of real case study examples (Amsterdam and the U.S.), while in SD_2 an artificial market is created between expansionists and conservationists who want to buy open land – either in order to turn it into urban area or to conserve it. In cellular automata, prices for housing are not explicitly included. Probabilities for land use change can be regarded as bids for (re-)development (CA_2). In some of the agent-based models, real estate markets are already included or are planned to be included (e.g., ABM_1, ABM_3, ABM_5). In these models, developers are agents who can influence the market and therefore also the prices. Governmental planning processes are never explicitly represented in a way that governmental agencies are actors within the model. In some models, planning decisions are integrated as a part of the scenario configuration, e.g., by restricting or promoting possible evolution paths for certain grid cells (e.g., MOLAND). In others, construction and demolition are exogeneous variables (Nijkamp *et al.*, 1993). But in these cases, planning decisions or housing market trends are not changed during the simulation, so that no feedbacks are established.

5 Conclusions

The main purpose of this review was to analyse causalities and feedback loops in current urban land use change models. Therefore, we analysed 19 simulation models stemming from four different simulation methodologies: spatial economics, system dynamics, cellular automata, and agent-based modelling. The main conclusion of this review is that there is a range of comprehensive urban land use change models but no unique approach to represent urban landscapes and human–nature interactions. Each author or working group has its own view and focuses on other parts of the urban system and the relationships within that system. Thus, the landscape aspect is of minor importance. Most of the approaches bear the potential to model local and regional urban processes, as they provide a multitude of components and variables. However, currently only a few models integrate direct or indirect feedback loops from environmental and landscape-related impacts of urban land use change on environment to the respective driving forces in the human sphere of the systems. We see the reason for this in the gap between social science methods and findings, and computational models (cf. Geist and Lambin, 2004, 2002). The former comprehensively cover behavioural heuristics on decision making but are often qualitative in nature. The latter need quantitative (sometimes spatially explicit) input data or at least simple rules to be coded and thus incorporated into the models. To bring both approaches together and to better incorporate qualitative, social science data into quantitative models is still one of the major challenges of urban land use and landscape modelling. This is a challenge, not only for modellers, since empirical data for formulating a resilient feedback loop, resulting from environmental impacts on human quality of life and decision making, is rarely available (Haase and Haase, 2008). As urban systems are open systems which do not depend on local or regional natural resources and ecosystem services, neither individual nor policy decisions strongly depend on the availability and state of nature of the surroundings (cf. Haase and Nuissl, 2007). This makes it more difficult to elicit and formalise resilient feedbacks from the environment or landscape back to the driver. Another challenge is to express urban land use relationships, and in particular the aforementioned decision making in a spatially explicit way, as most of the CA models under review do. Finally, relationships between the local and regional scale are realised only with respect to housing markets, as single choices on the local scale are able to influence regional markets and vice versa. None of the models deals with all possible linkages between “the built-up urban” and “the rural” landscape within an urban region, although CA models such as MOLAND cover both types of land use, at least in terms of land use types. Current “hotspots” of the worldwide agri-environmental discussion, such as biofuels and organic farming, should also be partially incorporated into urban models. Here, we see another way to introduce more landscape aspects into urban land use modelling.

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7 Annex

Within the following tables (describing the models in alphabetical order), empty cells indicate that no information was found in the literature on this issue. "–" in a cell means that this issue is not applicable to the model in question.

Field "Duration of model run:"

- C: Calibration to fit model parameters
- S: Scenarios for projections of future trends
- V: Validation using independent data

Table 3: Household life cycle model for residential relocation behaviour [SE_1]

Name of model	Household life cycle model for residential relocation behaviour			
Sources	Nijkamp *et al.* (1993)			
Technical data				
Application area	Covered area, physical boundaries	Case study: Greater Amsterdam Area	Extent of area	350 square miles / About 800,000 people
	Spatial units	20 zones	Size or grain of grids/zones	–
Time horizon	Time step	1 year	Duration of model run	1971 – 1984
Modelling approach	Simulation technique	Spatial economics	Qualitative or quantitative	Quantitative
Contents				
Main purpose	Modelling household life cycles and their impact on residential relocation behaviour and the urban housing market for a European capital city.			
Main variables with relationships	(1) households, (2) migration, (3) occupancy, (4) housing demand, (5) dwelling supply in zones and dwelling types, (6) allocation of households.			
	Domain	Not explicitly	Temporal range	–
Human decision making	Typology (classes) of agents?	Allocation of household	→ if yes: what types?	Households: single, 2-person household, 3-person household, 4+ person household, non-household
	Decision algorithm	Rational choice, maximum utility	Input into decision	Population and household data
Goals	Authors' opinion	Successful runs, validation and scenarios.		
Model development process	Concept	Given	Quantification of relationships	Empirical data

Table 4: Simulation of demographic changes and the housing market [SE_2]

Name of model	Simulation of demographic changes and the housing market			
Sources	Mankiw and Weil (1989)			
Technical data				
Application area	Covered area, physical boundaries	U.S. cities (census)	Extent of area	– / 203,190 people / 74,565 households
	Spatial units	U.S. cities (census)	Size or grain of grids/zones	–
Time horizon	Time step	1 year	Duration of model run	1970 – 2007 or 2020
Modelling approach	Simulation technique	Spatial economics	Qualitative or quantitative	Quantitative
Contents				
Main purpose	Simulation of demographic changes (baby boom and baby bust) and its influences on the housing market in the U.S.			
Main variables with relationships	(1) population, (2) households, (3) housing market (demand, prices), (4) economy (GNP)			
Human decision making	Domain	Not explicitly	Temporal range	–
	Typology (classes) of agents?	Allocation of household	→ if yes: what types?	Dummy household
	Decision algorithm	Rational choice, maximum utility	Input into decision	Census data
Goals	Authors' opinion	Successful runs, validation and scenarios.		
Model development process	Concept	Given	Quantification of relationships	Empirical data

Table 5: A System Dynamics Approach to Land Use / Transportation System Performance Modeling [SD_2]

Name of model	A System Dynamics Approach to Land Use / Transportation System Performance Modeling			
Sources	Haghani *et al.* (2003a,b)			
Technical data				
Application area	Covered area, physical boundaries	Varies with application area; Case study: Montgomery County	Extent of area	– / About 800,000 people
	Spatial units	U.S. cities (census)	Size or grain of grids/zones	–
Time horizon	Time step	1 year	Duration of model run	C: 1970 – 1980 V: 1980 – 1990
Modelling approach	Simulation technique	Spatial economics	Qualitative or quantitative	Quantitative
Contents				
Main purpose	Integrated land-use and transportation model for estimating scenarios regarding transport policies			
Main variables with relationships	Seven sub-models: (1) population, (2) migration, (3) household, (4) job growth, employment and commercial land development, (5) housing development, (6) travel demand and (7) congestion.			
	Domain	Not explicitly	Temporal range	–
Human decision making	Typology (classes) of agents?	Cohorts within population submodel	→ if yes: what types?	Persons: age 0–17, 18–44, 45–64, 65 male and female / Households: single, married with children, married without children, male or female with children, other
	Decision algorithm	–	Input into decision	–
Goals	Authors' opinion	First step is achieved, successful validation and scenarios.		
Model development process	Concept	Not stated	Quantification of relationships	Empirical data

Table 6: CLUE-s (Conversion of Land Use and its Effects) [CA_1]

Name of model	CLUE-s (Conversion of Land Use and its Effects)			
Sources	Verburg and Overmars (2007)			
Technical data				
Application area	Covered area, physical boundaries	User-specified / Several examples published	Extent of area	User-specified
	Spatial units	CLUE: soft-classified data (large pixels with fraction of land-uses)	Size or grain of grids/zones	User-specified / CLUE: 7 to 32 km / CLUE-s: 20 to 1,000 m
Time horizon	Time step	Iterative process stops when demand for land-use meets allocated area	Duration of model run	–
Modelling approach	Simulation technique	Cellular automata	Qualitative or quantitative	Quantitative
Contents				
Main purpose	Tool for understanding land-use patterns, possible future scenarios for given demand			
Main variables with relationships	Input: Pre-defined change in demand for land by different sectors for whole simulation area → CLUE-s assigns new land-uses per grid Each cell: most preferred land use based on suitability of location and competitive advantage of different land use types (demand), check: is land use change allowed? If no: next most preferred land use is chosen			
Human decision making	Domain	Not explicit decision making	Temporal range	–
	Typology (classes) of agents?	–	→ if yes: what types?	–
	Decision algorithm	–	Input into decision	–
Goals	Authors' opinion	Case-study specific		
Model development process	Concept	Not mentioned	Quantification of relationships	User-specified: empirical analysis, expert knowledge, spatial interactions, conversion elasticities

Table 7: CUF-2 (California Urban Futures) [CA_2]

Name of model	CUF 2 (California Urban Futures)			
Sources	Landis and Zhang (1998a,b)			
Technical data				
Application area	Covered area, physical boundaries	San Francisco Bay Area (California)	Extent of area	1.8 million ha
	Spatial units	Grid cells	Size or grain of grids/zones	100 × 100 m
Time horizon	Time step	Econometric: 10 years / Probabilities for land use change: once per simulation	Duration of model run	C: 1985 – 1995 / S: ?
Modelling approach	Simulation technique	Cellular automata	Qualitative or quantitative	Quantitative
Contents				
Main purpose	Simulating urban growth, scenarios for future development			
Main variables with relationships	Top-down approach: future trends of population, household, jobs → are assigned to grid cells Econometric models predict future population, households, employment (10 year intervals) LUC-model: estimates probabilities for land use change out of historical data, and simulation engine assigns probabilities to cells Probability of land use change (multinomial logit models) for a cell from i to j = f (initial site use, site characteristics, site accessibility, community characteristics, policy factors, relationships to neighbouring sites) → probabilities are interpreted as bids for (re-)development → population and jobs are assigned to cells by bids 7 urban land-use categories: undeveloped, single-family residential, multi-family residential, commercial, industrial, transportation, public			
Human decision making	Domain	Not explicit decision making	Temporal range	–
	Typology (classes) of agents?	–	→ if yes: what types?	–
	Decision algorithm	–	Input into decision	–
Goals	Authors' opinion	Achieved		
Model development process	Concept	Not mentioned	Quantification of relationships	Calibration using maps of land use change

Table 8: CURBA (California Urban and Biodiversity Analysis)(CA_3]

Name of model	CURBA (California Urban and Biodiversity Analysis)			
Sources	Landis *et al.* (1998)			
Technical data				
Application area	Covered area, physical boundaries	San Francisco Bay Area (California)	Extent of area	See CUF-2
	Spatial units	Grid cells	Size or grain of grids/zones	100 × 100 m
Time horizon	Time step		Duration of model run	
Modelling approach	Simulation technique	Cellular automata	Qualitative or quantitative	Quantitative
Contents				
Main purpose	Development of policy scenarios of urban growth, impact on habitat change/biodiversity			
Main variables with relationships	Two components: (1) urban growth model and (2) policy simulation and evaluation model / Urban growth model is based upon CUF-2 Policy simulation and evaluation: several growth scenarios → impact on habitat change and habitat fragmentation			
Human decision making	Domain	No explicit decision making	Temporal range	-
	Typology (classes) of agents?	–	→ if yes: what types?	–
	Decision algorithm	–	Input into decision	–
Goals	Authors' opinion	Achieved		
Model development process	Concept	See CUF-2	Quantification of relationships	See CUF-2

Table 9: ILUMASS (Integrated Land-Use Modelling and Transportation System Simulation) [ABM_1]

Name of model	ILUMASS (Integrated Land-Use Modelling and Transportation System Simulation)			
Sources	Strauch *et al.* (2003); Moeckel *et al.* (2006)			
Technical data				
Application area	Covered area, physical boundaries	Dortmund and its 25 surrounding municipalities	Extent of area	About 2,000 km^2 / 2.6 million people
	Spatial units	Statistical zones (total: 246) and grid cells	Size or grain of grids/zones	Grid cells: 100 × 100 m
Time horizon	Time step	One year	Duration of model run	S: 2000 – 2030
Modelling approach	Simulation technique	Coupled simulation system including agent-based simulations	Qualitative or quantitative	Quantitative
Contents				
Main purpose	Dynamic simulation model with a focus on urban traffic flows, including activity behaviour, changes in land use, and effects on environment			
Main variables with relationships	Five modules (+ integration module): 1. changes in land use, 2. activity patterns and travel demand, 3. traffic flows, 4. goods transport, 5. environmental impacts of transportation and land use Land use → demand for spatial interaction (work, shopping trips, etc.) → traffic → environmental impacts Feedbacks: (a) transport → accessibility of locations → location decisions of households, firms, developers. (b) environmental factors → location decisions (e.g., clean air, traffic noise) Land use module: moving households, location of firms, investment of developers, new industrial area			
Human decision making	Domain	Various, e.g., transport, household location, daily activity plans	Temporal range	Depending upon domain (daily travel behaviour vs. moving)
	Typology (classes) of agents?	Yes	→ if yes: what types?	Not mentioned
	Decision algorithm	Various (Markov, Logit, Monte-Carlo)	Input into decision	Depending upon domain, feedbacks included
Goals	Authors' opinion	Time of report: work in progress, later papers all focus on single modules		
Model development process	Concept	Not mentioned	Quantification of relationships	Not mentioned

Table 10: ILUTE (Integrated Land Use, Transportation, Environment model) [ABM_2]

Name of model	ILUTE (Integrated Land Use, Transportation, Environment model)			
Sources	Salvini and Miller (2005); Miller *et al.* (2004)			
Technical data				
Application area	Covered area, physical boundaries	Tests for Toronto area	Extent of area	5 million people
	Spatial units	Two versions: grids and buildings	Size or grain of grids/zones	2 parallel approaches: Grid: 30 × 30 m / Buildings as objects
Time horizon	Time step	Varying with submodels	Duration of model run	V: 1986 – 2001 / S: 10 – 20 years into future
Modelling approach	Simulation technique	Agent-based simulation	Qualitative or quantitative	Quantitative
Contents				
Main purpose	Evolution of an entire urban region with emphasis on transport			
Main variables with relationships	Land development → location choice → activity schedule → activity patterns → back to land development and all other variables in chain transportation network → automobile ownership → travel demand → network flows → back to transportation network and all other variables in chain influences			
Human decision making	Domain	Activity/travelling scheduling, route choice, real estate market, behaviour of economy, land development, household ownership	Temporal range	Depends upon domain. E.g.: typical travel day is computed once per simulation year per agent type.
	Typology (classes) of agents?	Yes	→ if yes: what types?	For households, individuals, firms
	Decision algorithm	Rule-based: reducing number of choices / logit model for selecting the “best” option	Input into decision	Not mentioned
Goals	Authors’ opinion	Work in progress		
Model development process	Concept	Not mentioned	Quantification of relationships	Empirical data

Table 11: Modelling biodiversity and land use [SD_3]

Name of model	Modelling biodiversity and land use			
Sources	Eppink *et al.* (2004)			
Technical data				
Application area	Covered area, physical boundaries	No explicit representation of a specific area. Urban region with surrounding area including wetlands	Extent of area	–
	Spatial units	No spatial resolution	Size or grain of grids/zones	–
Time horizon	Time step	1 year	Duration of model run	S: 100 years
Modelling approach	Simulation technique	System dynamics	Qualitative or quantitative	Qualitative
Contents				
Main purpose	Assessing the impact of urban sprawl on wetland biodiversity and social welfare			
Main variables with relationships	Population growth within city → higher population density and more need for agricultural land → expansionists attempt to buy surrounding area → change of wetland area to urban area & more agriculture decrease wetland biodiversity → conservationists' valuation of remaining biodiversity increases → conservationists buy wetland area for nature protection			
Human decision making	Domain	Human decision making is represented within system dynamics equations	Temporal range	1 year
	Typology (classes) of agents?	Yes	→ if yes: what types?	Expansionists, conservationists (see above) and owners of land
	Decision algorithm	Land is sold to the highest bidder	Input into decision	Prices offered by conservationists and expansionists.
Goals	Authors' opinion	First step for improving relationship between economic development and biodiversity		
Model development process	Concept	Not mentioned	Quantification of relationships	Not mentioned

Table 12: MOLAND [CA_4]

Name of model	MOLAND			
Sources	Engelen *et al.* (2007)			
Technical data				
Application area	Covered area, physical boundaries	Several examples across Europe and elsewhere	Extent of area	User-specified
	Spatial units	global: 1 zone / regional: zones, typically NUTS / local: grid cells	Size or grain of grids/zones	User-specified
Time horizon	Time step	annual	Duration of model run	C: last 40 – 50 years / S: user-specified, normally 30 years
	Simulation technique	Mainly rule-based cellular automata	Qualitative or quantitative	Quantitative
Contents				
Main purpose	To monitor developments of urban areas and identify trends at the European level, focus is on growth scenarios			
Main variables with relationships	Growth of economy and population (global level) → growth in competing regions (regional level), sets boundaries for all cells in a region → rules for land use change at the grid level: physical suitability, institutional suitability (e.g., planning documents), accessibility (via transport network), dynamics at the local level (land use functions attracting or repelling each other) Feedback from grid level to regional level: spatial distribution leads to quality and availability of space for different activities, which influences comparative attractiveness of a region			
Human decision making	Domain	No explicit decision making	Temporal range	–
	Typology (classes) of agents?	–	→ if yes: what types?	–
	Decision algorithm	–	Input into decision	–
Goals	Authors' opinion	Achieved		
Model development process	Concept	Not mentioned	Quantification of relationships	Calibration with historical data

Table 13: PUMA (Predicting Urbanisation with Multi-Agents) [ABM_3]

Name of model	PUMA (Predicting Urbanisation with Multi-Agents)			
Sources	Ettema *et al.* (2007)			
Technical data				
Application area	Covered area, physical boundaries	North Dutch Ranstadt (including Amsterdam, Utrecht, Schiphol airport)	Extent of area	3.16 million inhabitants
	Spatial units	Grid cells (and travel zones)	Size or grain of grids/zones	500 × 500 m
Time horizon	Time step	1 year / later: up to daily	Duration of model run	S: 2000 to approx. 2050
Modelling approach	Simulation technique	Agent-based simulation	Qualitative or quantitative	Quantitative
Contents				
Main purpose	Predicting urbanisation using behavioural agents			
Main variables with relationships	Demographic change → decisions of individuals → land use change / Not yet implemented: developers, authorities and firms/institutions (so far exogenous) [impact of household's decisions on land use not described]			
Human decision making	Domain	1. demographic events (no decisions, just stochastic) 2. residential relocation 3. job changes	Temporal range	Annual [Daily decisions in future work]
	Typology (classes) of agents?	Yes	→ if yes: what types?	Households: Number of adults and children; age of household head [dwellings are agents as well]
	Decision algorithm	Rational choice with utility maximisation	Input into decision	Residential relocation: characteristics of dwelling, commuting distance, socio-demographics / Job choice: salary, job type, distance to dwelling, personal preferences…
Goals	Authors' opinion	Promising approach, still work in progress		
Model development process	Concept	Empirical data	Quantification of relationships	Empirical data

Table 14: Rotterdam urban dynamics [SD_4]

Name of model	Rotterdam urban dynamics			
Sources	Sanders and Sanders (2004)			
Technical data				
Application area	Covered area, physical boundaries	Rotterdam	Extent of area	100,000 acres
	Spatial units	16 grid cells called “zones”	Size or grain of grids/zones	Squares with 3,125 miles each side
Time horizon	Time step		Duration of model run	S: 250 years
Modelling approach	Simulation technique	System dynamics	Qualitative or quantitative	Quantitative
Contents				
Main purpose	Redefining the model of urban dynamics by Forrester (1969), including: 1. spatial dimension (16 squares) and 2. disaggregation: different types of housing, industry, and people in zones			
Main variables with relationships	Bi-directional causal loops between: population, housing availability, houses, land availability, business structures, and job availability (linked with population) / Two markets: labor market and housing market compete for land / (no transportation)			
Human decision making	Domain	No explicit decision making	Temporal range	–
	Typology (classes) of agents?	–	→ if yes: what types?	–
	Decision algorithm	–	Input into decision	–
Goals	Authors’ opinion	Case of Rotterdam only as an example for generic results		
Model development process	Concept	Not mentioned	Quantification of relationships	Out of statistical data and expert knowledge

Table 15: SCOPE (South Coast Outlook and Participation Experience) [SD_5]

Name of model	SCOPE (South Coast Outlook and Participation Experience)			
Sources	Onsted (2002)			
Technical data				
Application area	Covered area, physical boundaries	South Coast of Santa Barbara County	Extent of area	137,000 acres / Approx. 200,000 inhabitants
	Spatial units	No spatial resolution	Size or grain of grids/zones	–
Time horizon	Time step		Duration of model run	V: 1960 – 2000 / S: 2000 – 2040
Modelling approach	Simulation technique	System dynamics	Qualitative or quantitative	Quantitative
Contents				
Main purpose	Simulation model to provide scenarios for future land use in Santa Barbara, e.g., with restrictions to urban growth			
Main variables with relationships	Five sectors: housing, population, business, quality of life, land use			
Human decision making	Domain	No explicit decision making	Temporal range	–
	Typology (classes) of agents?	–	→ if yes: what types?	–
	Decision algorithm	–	Input into decision	–
Goals	Authors' opinion	Achieved, but should still become more differentiated.		
Model development process	Concept	Expert knowledge	Quantification of relationships	Assumptions and statistical data

Table 16: Simulation of polycentric urban growth dynamics through agents [ABM_4]

Name of model	Simulation of polycentric urban growth dynamics through agents			
Sources	Loibl *et al.* (2007)			
Technical data				
Application area	Covered area, physical boundaries	Austrian Rhine valley with medium-sized centres and rural villages	Extent of area	7,330 hectares built-up area / 260,000 inhabitants
	Spatial units	Grid cells	Size or grain of grids/zones	50 × 50 m cells
Time horizon	Time step	Simulation stops when certain household, population and workplace growth numbers are achieved	Duration of model run	V: 1990 – 2000 / S: user-specified
Modelling approach	Simulation technique	Agent-based simulation	Qualitative or quantitative	Quantitative
Contents				
Main purpose	Development of built-up area in peri-urban region, driven by households and entrepreneurs; urban growth with different growth rates			
Main variables with relationships	Initialisation: increase of household and workplace numbers is defined 1. Municipality choice depending on regional attractiveness criteria (numbers of people, households and workplaces in the start of the year, average travel time to district centres and capital city, average share of attractive land-use classes in the municipality (open space, forest area) → household growth and workplace growth per municipality → transformation of absolute values into relative search frequencies → agents choose municipality via discrete choice 2. Local target area search: start with random cell, choosing most attractive cell 3. land use change (new built-up area, higher density) → influencing local attractiveness			
	Domain	Causing the construction of new built-up area or the densification of existing area, no moving as 'exchange' of dwellings	Temporal range	Long-term (moving / start-up of companies)
Human decision making	Typology (classes) of agents?	Yes	→ if yes: what types?	Four household types (1, 2, 3 or 4 persons) and two entrepreneurs (small and large)
	Decision algorithm	Discrete choice	Input into decision	Regional and local attractiveness
Goals	Authors' opinion	Achieved		
Model development process	Concept	Empirical data	Quantification of relationships	Empirical data

Table 17: SLEUTH (Slope, Landuse, Exclusion, Urban Extend, Transportation and Hillshade) [CA_5]

Name of model	SLEUTH (Slope, Landuse, Exclusion, Urban Extend, Transportation and Hillshade)			
Sources	Clarke *et al.* (1997); Silva and Clarke (2002); Dietzel and Clarke (2007)			
Technical data				
Application area	Covered area, physical boundaries	Numerous applications, mostly U.S.	Extent of area	User-specified
	Spatial units	Grid cells	Size or grain of grids/zones	Input for model: 8-bit GIF (100 × 100 m cells can be converted)
Time horizon	Time step	1 year	Duration of model run	C: at least 4 time steps / S: User-specified
Modelling approach	Simulation technique	Cellular automata	Qualitative or quantitative	Quantitative
Contents				
Main purpose	Modelling urban growth, scenarios for future development of an urban region			
Main variables with relationships	Two components (use depends on available data): (1) Urban growth: cells have one of two states: urban or non urban (2) Urban land use change with different land-use types Four types of growth behaviour: spontaneous, diffusive (with new growth centres), organic (into surroundings) and road-influenced Five main coefficients: diffusion, breed, spread, slope, and road coefficient (need to be calibrated for each case study) Self modification rules: e.g., concerning the kind of exponential or S-curve growth; denser road network → road gravity factor increases; land availability decreases → slope resistance factor is decreased (more hilly areas); spread factor increases over time			
Human decision making	Domain	No explicit decision making	Temporal range	–
	Typology (classes) of agents?	–	→ if yes: what types?	–
	Decision algorithm	–	Input into decision	–
Goals	Authors' opinion	Achieved		
Model development process	Concept	Not mentioned	Quantification of relationships	Calibration using historical maps

Table 18: Urban dynamics [SD_1]

Name of model	Urban dynamics			
Sources	Forrester (1969); Alfeld (1995)			
Technical data				
Application area	Covered area, physical boundaries	Either suburban or core area (Forrester 1969: 2) / Examples mentioned in Alfeld, 1995: Lowell, Boston, Concord, Marlborough, Palm Coast	Extent of area	User-specified
	Spatial units	No spatial resolution	Size or grain of grids/zones	–
Time horizon	Time step		Duration of model run	S: Up to 250 years
Modelling approach	Simulation technique	System dynamics	Qualitative or quantitative	Quantitative
Contents				
Main purpose	Modelling urban system in general, explicitly including “urban decline.” Examples: focus on a specific topic, e.g., rapid population growth, demolition, et cetera, and therefore need specific models.			
Main variables with relationships	Original model by Forrester: Three subsystems: business, housing, population			
Human decision making	Domain	No explicit decision making	Temporal range	–
	Typology (classes) of agents?	–	→ if yes: what types?	–
	Decision algorithm	–	Input into decision	–
Goals	Authors’ opinion	Achieved		
Model development process	Concept	Expert knowledge	Quantification of relationships	Statistical data and own estimation

Table 19: Urban transformation process in the Haaglanden region [SD_6]

Name of model	Simulating the urban transformation process in the Haaglanden region in the Netherlands			
Sources	Eskinasi and Rouwette (2004)			
Technical data				
Application area	Covered area, physical boundaries	The Haaglanden region, including the Hague and surrounding suburbs	Extent of area	
	Spatial units	No spatial resolution	Size or grain of grids/zones	–
Time horizon	Time step		Duration of model run	S: 1998 – 2010
Modelling approach	Simulation technique	System dynamics	Qualitative or quantitative	Qualitative
Contents				
Main purpose	Assessing the impact of future policy interventions on the social housing market (specific: rate of building new dwellings)			
Main variables with relationships	Four stocks: 1 Commercial housing stock 2 Social housing stock 3 Waiting families 4 Supply of available social houses Processes involved: Migration, demolition, construction			
Human decision making	Domain	No explicit decision making	Temporal range	–
	Typology (classes) of agents?	–	→ if yes: what types?	–
	Decision algorithm	–	Input into decision	–
Goals	Authors' opinion	Model is useful for its goal		
	Validation	No (but impact of process on stakeholders is monitored)	Plausibility analysis	With stakeholders
Model development process	Concept	Participation of stakeholders, narrative approach	Quantification of relationships	Empirical data or expert guesses.

Table 20: Urban travel system [SD_7]

Name of model	A system dynamics model for the urban travel system			
Sources	Raux (2003)			
Technical data				
Application area	Covered area, physical boundaries	Hypothetical city	Extent of area	–
	Spatial units	No spatial resolution	Size or grain of grids/zones	–
Time horizon	Time step		Duration of model run	S: 20 years into the future
Modelling approach	Simulation technique	System dynamics	Qualitative or quantitative	Quantitative
Contents				
Main purpose	To simulate medium- and long-term effects of urban transport policies with reference to sustainable travel			
Main variables with relationships	Seven major blocks: urbanisation, internal travel demand (trips within system), car ownership, external travel demand (inflowing, outflowing and through traffic), transportation (comparing supply and demand) and evaluation (socioeconomic and environmental appraisals)			
Human decision making	Domain	No explicit decision making	Temporal range	–
	Typology (classes) of agents?	–	→ if yes: what types?	–
	Decision algorithm	–	Input into decision	–
Goals	Authors' opinion	Work in progress		
Model development process	Concept	Expert knowledge	Quantification of relationships	Expert knowledge and statistical values

Table 21: UrbanSim [ABM_5]

Name of model	UrbanSim			
Sources	Waddell (2006); Waddell *et al.* (2003)			
Technical data				
Application area	Covered area, physical boundaries	Several examples in the U.S., Europe and Asia	Extent of area	User-specified
	Spatial units	Initially: mixture of parcels and zones / later: grid	Size or grain of grids/zones	User-specified / Cell: 150 × 150 m regarded as default
Time horizon	Time step	1 year	Duration of model run	User-specified
Modelling approach	Simulation technique	Coupled simulation models including agent-based simulations	Qualitative or quantitative	Quantitative
Contents				
Main purpose	Link between transportation and land use; impact of different planning strategies			
Main variables with relationships	Exogenous: (1) macroeconomics (population, employment) and (2) travel demand (travel conditions). Six models: 1 Accessibility (output: access to workplaces and shops for each cell) 2 Transition (output: number of new jobs and new households per year) 3 Mobility (output: number of moving (existing) jobs / households) 4 Location (output: location of new or moving jobs / households) 5 Real Estate Development (output: land use change) 6 Land price (output: land prices)			
Human decision making	Domain	Mobility and location	Temporal range	Depends on issues
	Typology (classes) of agents?	Initially households / firms, later persons / jobs	→ if yes: what types?	User-specified
	Decision algorithm	Multinomial logit model	Input into decision	Land-use itself, socio-demographics, dwellings
Goals	Authors' opinion	Achieved		
Model development process	Concept	Not mentioned	Quantification of relationships	Out of empirical data

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