Land-use scenario modelling based on human decisions – Combining system dynamics and cellular automata

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Steffen Lauf1, Dagmar Haase2, Birgit Kleinschmit1
1Technische Universität Berlin, Dept. of Geoinformation in Environmental Planning, Berlin, Germany
2Humboldt University of Berlin, Dept. of Landscape Ecology, Berlin, and Helmholtz Centre for Environmental Research – UFZ, Germany
steffen.lauf@tu-berlin.de

Abstract: Our paper introduces a combined model approach using system dynamics simulating regional drivers and cellular automaton representing local land-use dynamics. The model benefits from conclusive causal interrelations of detailed population dynamics, real household decision parameters, residential demand on prevailing residential land use types and residential supply as a result of dynamic housing parameters. Consequently, we can simulate growth and shrinkage processes to occur concurrently within an urban region. In this process, human decisions are covered in two ways, firstly, by bottom-up individual residential choice-making over different residential types and secondly by top-down decision making by planning authorities. The model is applied to the metropolitan region of Berlin. It provides more plausible results compared to cellular automata approaches using conventional trend based regional input models. Human decisions on land-use are displayed in six scenarios representing possible future paths of Berlin’s urban development from 2008 to 2030. The findings indicate that the effect on residential patterns due to different planning approaches is equal to the effect introduced by the likely maximum deviation of economic and demographic trends as proved by kappa values. A quality assessment confirms the benefit of the combined approach and affirms that the model functionality is sound.

Keywords: Urban region, land-use model, system dynamics, cellular automaton, scenario simulations, Berlin

1 INTRODUCTION

Changing land use has an important impact on the environment Therefore, both drivers and effects must be considered systematically and reciprocally to understand their interrelations and dynamics at the local and regional levels [Batty 2007]. For this purpose, model approaches are highly relevant. Numerous land-use-scenario models are applied to support policy making by estimating future developments and environmental effects due to land-use change (LUC) [Schwarz et al. 2010]. With respect to land use, cities exhibit highly complex dynamics that often result in both environmental and social problems. Rising imperviousness, loss of agricultural land and green spaces, danger for human health and social segregation are among the problems to be addressed [Forman 2008]. For forward planning at the local and regional levels, processes and feedbacks of LUC should be analyzed using spatial urban models for scenario forecasts that will lead to early intervention policies and adaptations, thus mitigating negative effects.
1.1 Objectives

We present an integrated LUC model applying system dynamics (SD) for regional dynamics and a cellular automaton (CA) for local dynamics from what we expect to profit their respective strengths, such as the reproduction of detailed and highly dynamic causal interrelations within SD [Seppelt 2003] and the spatial explicitness and neighbourhood analysis of CA [Batty 2007]. Furthermore, we want to close the gap of deficiently considered population dynamics with regard to current trends of demographic change implying major impact on urban LUC [Buzar et al. 2005]. Thereby, we focus on modelling growth and shrinkage processes within cities that might even occur simultaneously in different residential uses as recently proved for many western cities [Kroll and Haase 2010]. For this purpose we require a more sophisticated classification of residential land-uses that represents different urban structure types (UST) and offers greater detail of a diverse housing market. Moreover, we are interested in the effects of human decision-making on LUC from two perspectives, representing bottom-up and top-down decisions. Firstly we aim to capture the effects on LUC by individual household decisions for residential choice, and secondly the effect of human decisions on LUC by policy makers and planning authorities. Finally, we show possible paths of urban development for the metropolitan region of Berlin to 2030. Within different scenarios we observe urban pattern shifts and LUC based on different population, economic and planning specifications. In this context, we analyse the influence of future LUC on space consumption and the development of agricultural and natural land.

2 THE MODEL

The proposed model incorporates the functional relation of urban land-use development and household dynamics. Residential choice is implemented applying household-related preferences with respect to relevant housing decision variables (Figure 1: SD). We particularly focus on residential uses as major urban change refers to residential dynamics [Batty 2007].

One of the main drivers of LUC is population dynamics, whereas not only the total population number but also the household structure directs urban LUC [Haase et al. 2010]. The second demographic transition is describing the change of traditional (larger) family households towards small single, childless couple and single-parent households, which are viewed as non-traditional household types. The effects are a decreasing mean household size and an increasing household number, leading to an increase of the total living space consumption at equal or even smaller population numbers [Buzar et al. 2005]. All integrated drivers for LUC are to be found in Figure 1 described as model input.

The model structure consists of a population and housing demand-supply model using SD and a CA land-use allocation model with spatial dynamics as a function of SD (Figure 1). For a detailed representation of land use dynamics a cell size of 50 x 50 m was chosen with 2.14 million cells representing the study area in a uniform grid. The regional SD model is implemented in the modeling environment Simile (version 4.7) by Simulistics [Costanza and Voinov 2004]. For the spatial dynamics, we applied the CA software package Metronamica from RIKS (Research Institute for Knowledge Systems) [e.g. Van Delden et al. 2007]. A detailed technical description of both sub models (SD and CA and its functionality) can be found in Lauf et al. [2011, 2012]. The output of the model consists of scenario based land-use maps in one-year steps from 2008 until 2030 (sect. 2.3) which were derived after a successful quality assessment proving the benefit of the model with regard to the reproduction of urban pattern dynamics (sect. 3.1).
2.1 Study area

The model is applied to the metropolitan region of Berlin. The area exceeds the administrative border of Berlin and involves parts of the federal state of Brandenburg. The inclusion of Berlin’s hinterland was chosen to capture urban and peri-urban relationships. The region includes 5.3 thousand km² of land and has a population of 4.4 million (with 3.4 million inhabitants in Berlin). As one of the larger and central European agglomerations, Berlin represents a case for an ageing population with changing household types as defined by demographic change [SenUD 1990-2009]. Furthermore, Berlin’s LUC is characterized by simultaneous growth and shrinkage, which are not just limited to outer (suburban) growth and inner decline but rather emerge next to each other and within the same area.

Figure 2. The metropolitan region of Berlin in 2008, the figure lists all land-use classes used and data on transportation covered in the model.
2.2 Calibration and validation

For the SD model we used regional census and housing data from 1992 to 2001 for all parameters as seen in Figure 1 including respective trends for the given time span [SOBB 1991-2008, SenUD 1990-2009]. For the calibration of the CA model two land-use maps were prepared (1992, 2008), derived from satellite imagery and an available biotope map. The study area was divided and only the area within the city borders of Berlin was used for calibration due to better data provision (covering 30% of the total area). Zoning and accessibility data are derived from current data.

The quality assessment of the coupled model is challenging because the time series are generally short (1992-2008) which results in striking validation measures such as kappa or mean relative deviation (MRD) due to relatively small changes. For the SD model we utilize MRD and correlations between observed and simulated data for 2008. A null model (NM) substituting the SD model was applied to test the performance of the model linkage using SD and CA [Pontius Jr. and Petrova 2010]. The NM calculates the total living space as a result of population with a constant growth rate and the mean living space consumption per capita (without a decision process), which then was translated into total residential area using the mean floor space index. The results were then read into the CA and distributed over all residential uses according to their overall ratios.

2.3 Scenarios

Future scenarios were analyses for 2008 to 2030 in annual steps. Scenario storylines follow the expected results of the maximum population range (cf. sect. 3.2) and the maximum economic range for 2030 [SOBB 1991-2008, SenUD 1990-2009]. As a result we implemented a shrinkage, a baseline (continuation of trends) and a growth scenario, controlled by the inputs of the SD model. To test the effects of human decision-making on urban patterns due to planning we also included two different planning regimes. The first includes planning standards only for the new airport transition. The second includes urban planning specifications by regional development and zoning plans. Consequently, six scenarios were generated in total.

3 RESULTS AND DISCUSSION

3.1 Model quality

The model was tested using observed data of 2008 and simulated data from the period 1992 to 2008. Before testing the spatially explicit model output of the CA, the quality of the SD model was tested. MRD values of less than 20% (mostly less than 10%) for each population age class, HHT and urban structure types confirm a good model fit which is additionally affirmed by the coefficients of determination ($R_{Pop}^2=0.82; R_{HHT}^2=0.89; R_{UST}^2=0.98$).

The final spatial allocation output (CA) was compared with the observed land-use data for both model combinations (NM+CA and SD+CA). Using NM provides a cell match of 90.4% for all residential classes, whereas 93.1% was achieved using the proposed SD model. The total difference of 6,944 residential cells was calculated comparing both model outputs with each other. Furthermore, a higher dispersion and fragmentation of new residential cells appeared for NM whereas for SD new residential cells originated closer to already existing residential areas. Table 1 proves more precise results using our proposed model (SD+CA) than using NM representative for conventional regional (macro) models for CA. However, the obtained kappa values have to be viewed critically due to the short simulation period and the general validation uncertainties using kappa values. Newly suggested quantity and allocation disagreement seem promising [Pontius and Millones 2011].
Table 1. Comparison results, simulated vs. observed, regarding residential uses where current land use of 2008 is compared with simulation results for the entire model using the null model and the proposed system dynamics model.

<table>
<thead>
<tr>
<th>Observed / Simulated</th>
<th>NM + CA</th>
<th>SD + CA (proposed model)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Kappa</td>
<td>k-Loc</td>
</tr>
<tr>
<td>Prefabricated multi-story houses</td>
<td>0.91 0.95 0.96</td>
<td>0.95 0.95 0.99</td>
</tr>
<tr>
<td>Multi-story rows houses</td>
<td>0.95 0.97 0.98</td>
<td>0.97 0.98 0.99</td>
</tr>
<tr>
<td>Wilhelminian blocks</td>
<td>0.95 0.98 0.98</td>
<td>0.97 0.98 1.00</td>
</tr>
<tr>
<td>Villas</td>
<td>0.95 0.98 0.97</td>
<td>0.98 0.98 1.00</td>
</tr>
<tr>
<td>Detached houses</td>
<td>0.95 0.98 0.97</td>
<td>0.93 0.93 0.99</td>
</tr>
<tr>
<td>Suburban village</td>
<td>0.61 0.63 0.97</td>
<td>0.96 0.96 1.00</td>
</tr>
<tr>
<td>Total residential area</td>
<td>0.91 0.92 0.98</td>
<td>0.90 0.93 0.99</td>
</tr>
</tbody>
</table>

3.2 Scenario simulations

Due to the fact of implementing varying economic and demographic scenarios we established differing population developments. The total population number varies from 4.74 million people for the growth scenarios (+6.84%) and 4.27 million people for the shrinkage scenarios (-3.73%) in 2030, (Baseline = 4.53 million people). In all scenarios, the effects of demographic change appear with different strength. On average, the share of persons older than 65 years increases from 19 to 25%, whereas the share of persons under 25-years decreases from 23 to 21%. The amount of people living in traditional family households decreases from 28 to 23%, whereas the amount of people living in small households or shared flats increases from 61 to 66%. Consequently, the mean household size decrease – which is associated with an increasing per capita need for living space – results in an increasing total residential area for all scenarios. This development is accompanied by the decrease of agricultural and natural land despite the possibilities of population stagnation or decline. A closer look at the quantitative changes of UST in Figure 3 reveals simultaneous processes of growth and shrinkage.

Figure 3. Urban structure types from 2008 to 2030 (SD outputs and CA inputs).

Prefabricated multi-story houses, mainly from socialistic times, show the biggest decline of more than 5.5% for all scenarios as they are less in demand than other types [Haase et al. 2010]. The majority of UST represent central residential uses except for detached houses and suburban village. Those central types are predominantly increasing which indicates a reurbanisation trend [Buzar et al. 2005]. This is confirmed by the simulated increase of smaller households and their housing decisions. Detached and semi-detached family houses represent quantitatively the strongest growth. The relatively high increase results in general from a very low floor space index (= ratio of living space and plot size). Nevertheless, this trend occurs despite decreasing family households in all scenarios. One reason is the simulated abandoned residential living space which is involved in the total residential area of each land use. Rising vacancy rates were ascertained for residential uses from growth to shrinkage scenarios within SD.

Figure 4 displays the simulated shift of built-up areas (residential, commercial and industrial areas; areas of public and private services, airports) between 2008 and
2030 for the scenario B2. The results display the urban expansion along radial developmental priority axes (mainly detached houses and commercial areas), new developments on the former central airports Tempelhof and Tegel (mainly central residential uses, commercial areas and urban green) and the new airport Berlin-Brandenburg International in the southeast with new commercial and residential areas. Further, we detected a loss of built-up areas in the hinterland (red patches). As was to be expected, the obtained kappa values are very high due to the large study area and the comparatively small changes after a simulation run of 22 years.

![Figure 4](image1.png)

**Figure 4.** Land-use map comparison 2008 (observed) and B2 2030; blue patches represent spread built-up areas, red patches represent abandoned built-up areas.

![Figure 5](image2.png)

**Figure 5.** Comparison of land-use maps S2 and G2 2030 (built-up areas).

![Figure 6](image3.png)

**Figure 6.** Comparison of land-use maps B1 and B2 2030 (built-up areas).

In Figure 5 we compared the outputs for the growth and shrinkage scenario under planning constraints to present the spatial span of future urban development. The main differences occur at the city edge where urban expansion proceeds within the growth scenario. Most of the red patches represent brownfields. Interestingly, some of the small central red patches depict residential uses which were not considered to be suitable in the growth scenario. This might be due to the small size of patches which is why areas with higher expansion potential were selected for cell allocation. Figure 6 shows the map comparison result for scenario B1 and B2 for the year 2030. Low planning standards (B1) result in clustering of new urban patches in the north of the city as a consequence of excellent accessibility to transportation. Smaller patches emerge dispersed in the whole study area including central areas.
of Berlin. Under strict planning standards (B2), new urban patches arise along the radial urban axes close to existing built-up areas. The new airport in the southeast exhibits a new development area especially for commercial and industrial areas but also for public and private services. The comparison of the kappa coefficients of Figure 5 and 6 reveals equal values. In Figure 5 we see a higher quantitative deviation of both maps (k-Histo) whereas Figure 6 shows a higher spatial deviation of both maps (k-Loc). It can be concluded for the simulated scenarios that differing planning standards and different population trends influence the urban pattern differently but with equivalent effects on the urban pattern. Figure 7 provides detailed information on the total and relative conversion by built-up areas. It becomes obvious that regardless of the scenarios most new developments occur on agricultural land (arable land and pasture). However, more arable land but less pasture is converted within the scenarios with strict planning standards (S2, B2, G2). Ecological valuable forests and shrubs are less affected. Yet, the question arises: which use is more profitable in terms of ecosystem services [MA 2005]. The different scenarios results reveal the exponential decline of valuable arable soils (of up to 5%) with growing population and economy, which are certainly crucial for provisioning services [MA 2005].

4 CONCLUSIONS

The proposed model represents an approach that addresses one of the current gaps in LUC modeling. The combination of SD and CA provides an enhancement of dynamic model behavior due to improved causal interrelations of system elements and drivers of LUC. Through the integration of more profound population and household dynamics, the effects of demographic change on residential land-uses are measurable. The model enables the simulations of growth and shrinkage processes to occur concurrently. The model has been applied to the metropolitan region of Berlin. The size of the study region represents a challenge because it is a
large and complex urban region that is dynamically displayed at a 50x50 m cell raster. A good data infrastructure is a prerequisite to making the model applicable to other urban regions or cities. Within empirically-grounded scenarios possible urban developments for 2030 were uncovered for the metropolitan region of Berlin. Obvious urban pattern shifts could be determined based on different population, economic and planning specifications. First results on space consumption and the developments of agricultural and natural land uses show the meaning of scenario simulation analysis. In further research we intend to use these scenario results to determine conflicts and trade-offs of relevant ecosystem services caused by LUC.

ACKNOWLEDGMENTS

This research is part of the Graduate Research Program 780/3 "Perspectives on Urban Ecology III" and is funded by the German Research Foundation. Special thanks are directed to Hedwig van Delden (RIKS) for cooperating.

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