Simulating land-use change in Portugal using an activity-based model

Jasper van Vliet and Hedwig van Delden

Research Institute for Knowledge Systems b.v., The Netherlands
(jvanvliet@riks.nl / hvdelden@riks.nl)

ABSTRACT

This paper presents an activity based land-use model, where activities represent quantitative information, such as population or jobs. These activities are added to a constraint cellular automaton (CA) model, which is now constrained in terms of their activities instead of their land use. The CA transition rules distribute activities based on the neighbouring activity distribution, the land use distribution, a diseconomies of scale term, some location properties and a stochastic perturbation term. Land use is then allocated according to the new activity distribution. Hence land use and activities are mutually dependent and each cell has two values: a land use state and a vector of activities. The activity based model is tested to simulate population dynamics and land-use changes in Portugal. Simulation results show that the model can produce realistic land use dynamics. Moreover, we argue that the inclusion of activities closer resembles the process of real world land-use dynamics and offers opportunities for integrated modelling due to the availability of quantitative information.

KEYWORDS: Land-use change, Activity-based modeling, Agent typologies, Urbanization

LAND-USE CHANGE AS A DYNAMIC SYSTEM

Because land use is constantly adjusting to changing biophysical and socio-economic conditions, it can be characterized as a dynamic system. This observation holds for rural areas as well as urban areas, and often the two are related. For example climate change forces some farmers to abandon their lands when local biophysical conditions change for the worse while the socio-economic conditions pull them to urban areas in search for employment.

Although some land-use changes are changes in natural land, a large part of the changes are caused by human influence (Parker et al., 2008) as it is eventually the farmer that decides to leave his land and it is the director of the company that decides to outsource activities to other locations. Such decisions are not made in isolation, but instead influence each other. For example, people consider the availability of public services or transportation networks when choosing where to live. These facilities, however, are there because of earlier decisions on developments in the vicinity.

These examples illustrate the general observation that land use, both urban and rural, is constantly changing. The land-use patterns one finds today are therefore essentially the result of a series of previous and incremental land-use changes. These feedback mechanisms can cause developments that are initially small to grow over time and reinforce each other, which makes the present land-use pattern highly path dependent (Brown et al., 2005). In order to gain insights in and explain land-use patterns it is therefore essential to consider processes instead of states only.

For reasons of practical, financial, and ethical consideration models are the appropriate way to study land-use change processes (Janssen and Ostrom, 2006). In line with Epstein's generative question (Epstein, 1999) we argue that these models should be able to generate land-use patterns through decentralized local interactions. In an earlier study (Van Vliet et al., accepted) the activity based model was presented, which is able to generate land use patterns from the bottom up. The aim of this study is to test this model on a real world application.

The next section introduces the concept of activity-based modelling that simulates land-use changes from the bottom up. Section three discusses an application that models land abandonment and urbanization patterns in Portugal using the activity based approach. Section four discusses the preliminary results of this application and some directions for future research.

BETWEEN CELLS AND AGENTS

Over the last decades several spatial explicit approaches for modelling land use have been proposed. An overview of different approaches is among others available in Veldkamp and Lambin (2001). From these approaches, we would like to consider two concepts in more detail: Multi Agent Systems (MAS) and Cellular Automata (CA) based models. Both concepts approach represent decision-making, allow for feedback over time and generate land-use patterns from local dynamics.

CA exist on a lattice, which makes them inherently spatial and therefore suitable for the simulation of land-use dynamics. In CA, the cell is the basic unit of computation and cell sizes can be adjusted according to the scope of the application. Therefore models can keep a computational efficiency, but this comes at the cost of detail. Simulating land-use changes at this rather high level of abstraction brings the advantage that CA have relatively low data demands. Although calibration and validation of these models has been considered a major issue, several calibrated examples are reported (Silva and Clarke, 2002; Barredo et al., 2004). The advantages of CA come at the cost of detail: individual actors are not considered. Instead cells have a state, which generally represents the predominant land use, and actors are represented indirectly through the land-use classes they make decisions about. Land uses are thus by definition mutually exclusive and mixed land uses can only exists superficially, when defined as a separate land use class. However, in reality mixed land use is the rule rather than the exception.

MAS differ from CA in that agents can represent actors separately from the lattice they exist on, such as individuals, households or companies. Actually, MAS in itself are not necessarily spatial, but agents can be linked to a location for example by their presence, ownership, or as farmer of the land. The advantage of MAS is that they can represent the behaviour of agents in a very straightforward way. Because agents are the basic unit of computation, MAS are computationally demanding. In addition, MAS require data on the level of agents, which makes them data demanding and which poses difficulties for model calibration and validation (Robinson et al., 2007). The problem of data collection is further thwarted by privacy regulations that are related to personal data.

Several efforts have been made to bridge the gap between CA and MAS by adding quantitative information to cellular land-use models. Wu and Webster (2000), Yeh and Li (2002) and Loibl and Tötzer (2003) all simulate urban growth in a dynamic and spatial environment by using density of development or population. These models are all aiming to simulate urbanization processes incrementally. Consequently, non-urban land uses are not actively modelled; they can influence the allocation of population or urban densification, but they do not change themselves except into urban land.

The activity-based approach

We generalize these ideas of modelling densities on a location as the *activity-based* approach (Van Vliet et al., accepted), where activities can represent different kinds of quantitative information, such as employment or inhabitants. In that sense we use the term *activities* similarly to travel demand modellers that use the location of activities such as work and residential locations as input (Davidson et al., 2007).

In the activity-based approach, a location on the lattice can have a predominant land use as well as a density for each activity. Although activities are clearly related to land-uses, this relation is not necessarily a one-to-one relation. The majority of the population is for example living in residential areas, but some are living in agricultural areas or in natural areas. At the other hand, some people also work in residential areas. The activity-based approach therefore separates the predominant land use on a location from the activities that take place there. This inherently allows for mixed land uses.

In this aspect the activity-based approach includes aspects from CA as well as MAS: land use and activities are cell properties and are computed on a cell basis. At the same time characteristics of agent typologies can be included and used for modelling differences in their behaviour. For example families with children, young urban professionals and retired couples can exists as activity types that together constitute the total population, and employment in services, commercial, and industry together comprise the employment on a location.

To generate land-use patterns time is represented in discrete steps, similar to most CA and MAS. Each time step, activities are redistributed as a function of the distribution of activities and land uses from the previous time step. Hence activities can increase or decrease each time step and on all locations. After that, land uses are allocated as a function of the new activity distribution and the previous land-use pattern.

This allows for incremental changes over time as for example peri-urban regions can be identified as agricultural first, but as the population increases it can change into residential eventually.

The activity-based approach as described was implemented in the Metronamica land-use modelling framework (RIKS, 2009). In an earlier study (Van Vliet et al., accepted) the activity based model was applied in a synthetic application to test its ability to grow realistic urbanization patterns. In this paper we present the implementation and the first results from a case study that tests its ability to simulate actual land-use dynamics.

IMPLEMENTATION OF THE ACTIVITY-BASED MODEL TO SIMULATE URBANIZATION AND LAND ABANDONMENT IN PORTUGAL

The implemented model includes four types of land uses: features, activity-constrained land uses, area-constrained land uses and unconstrained land uses. Features are land uses that do not change over the course of a simulation, such as marine water. Activity-constrained land uses are land uses that exist as a result of the activities on a location, such as residential land uses which exists by their population. The demand for activities is defined exogenously. Area-constrained land uses are those land uses for which the total area is constrained and defined exogenously, for example arable land. Unconstrained land uses finally are land uses that cover locations which are not used by another land use. A typical example is natural vegetation.

To keep track of activities, an additional data layer is required per type of activity. Hence a cell has no longer only one discrete cell state. Instead it has a land-use state and one numerical value for each activity. Computation of land-use dynamics therefore becomes a two-step process, as presented in figure 1. In each time step, first the demand for activities (a) is distributed according to the potential of each location for that activity (b), which is a function of the land use and activity distribution in the previous time step (c and d), as well as local characteristics of that location (e). Activity-constrained land uses are then assigned based on the updated activity distribution (f). Similarly, the total potential for area constrained land uses is computed based on the land use and activity distribution from the previous time step (g and h) and local characteristics of that location (i). Land uses are allocated accordingly (j) until the area demand (k) is fulfilled. The algorithms that are used in the computation of the potentials and in the allocation of activities and land uses are described in van Vliet et al. (accepted)

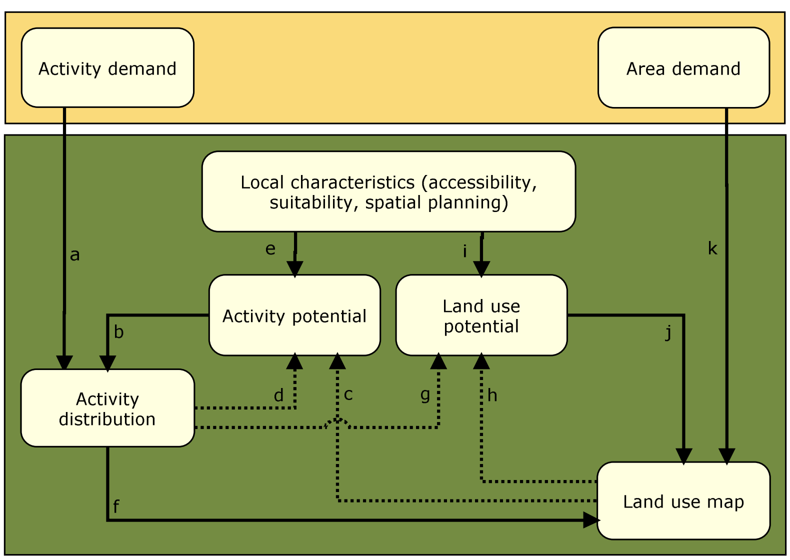

Figure 1: *System diagram of the implemented activity-based model (see text for explanation).*

Application of the activity-based model to simulate land-use changes in Portugal

The goal of this study was to simulate urbanization as a result of land abandonment. For this the activity-based model was applied to Portugal, which was represented on a lattice with cells of 1 km^2. Land-use data was taken from the Corine Land Cover database (Haines-Young and Weber, 2006). This data was reclassified into residential land (activity-constrained land use), forest, commercial and industrial, agriculture, and recreational land uses (area-constrained land uses), natural vegetation (vacant land use), water, wetlands, airports, and mining areas (feature land uses).

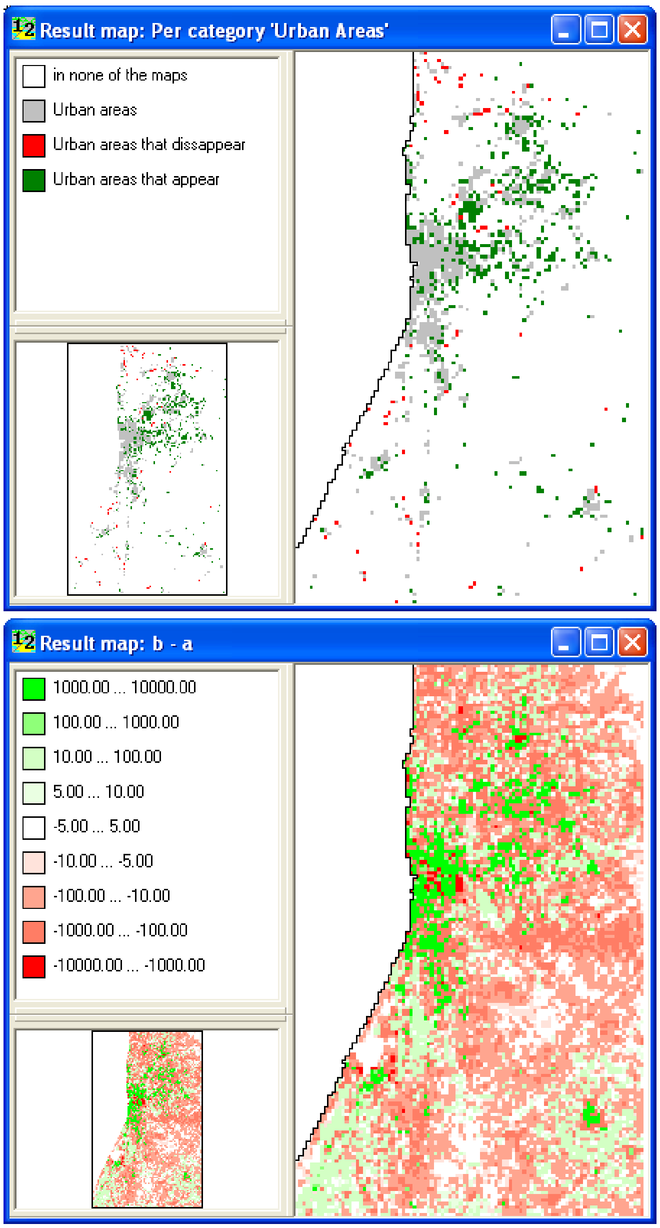

Figure 2: *Simulated urban land-use change between 2000 and 2040 on the top and simulated population change over the same period on the bottom. Urban land use comprises residential and industrial and commercial land uses combined.*

Population was modeled as an activity. This data was not measured directly but derived from the Corine Land Cover database (Gallego and Peedel, 2001). Due to data availability, no further subdivision was made to represent various population groups.

Because a dataset that include land use and population was only available for one year, we could not test the activity based model on its accuracy to simulate historic changes. Instead we used the model to simulate land-use patterns and population distribution for the year 2040. The results were subsequently tested on the ability to generate realistic results, which was assessed qualitatively on the type of land-use changes that are generated by the activity dynamics.

Figure 2 shows the change in urban land-use over the course of the simulation for a selected region around Porto. The figure shows a considerable urbanization and suburbanization around the central city, while at the same time a number of rural villages disappear. Figure 2 also shows the population changes for the same area. Underlying these dynamics is an incremental decrease of population density in the rural regions, and at the same time an increasing attraction of the urban areas. It should be noted that this was not input to the model but strictly the result of local activity dynamics.

Figure 3 shows the rank size distribution, otherwise known as Zipf's law (Cordoba, 2008) for the actual situation in 2000 and the simulated result for 2040. A comparison of the two indicates that although the total urban population has grown over time, a realistic size distribution is maintained. In fact, this distribution is identical in terms of its slope, Except that all urban clusters increased in size. This confirms the earlier observation that the activity based model generates realistic urbanization patterns.

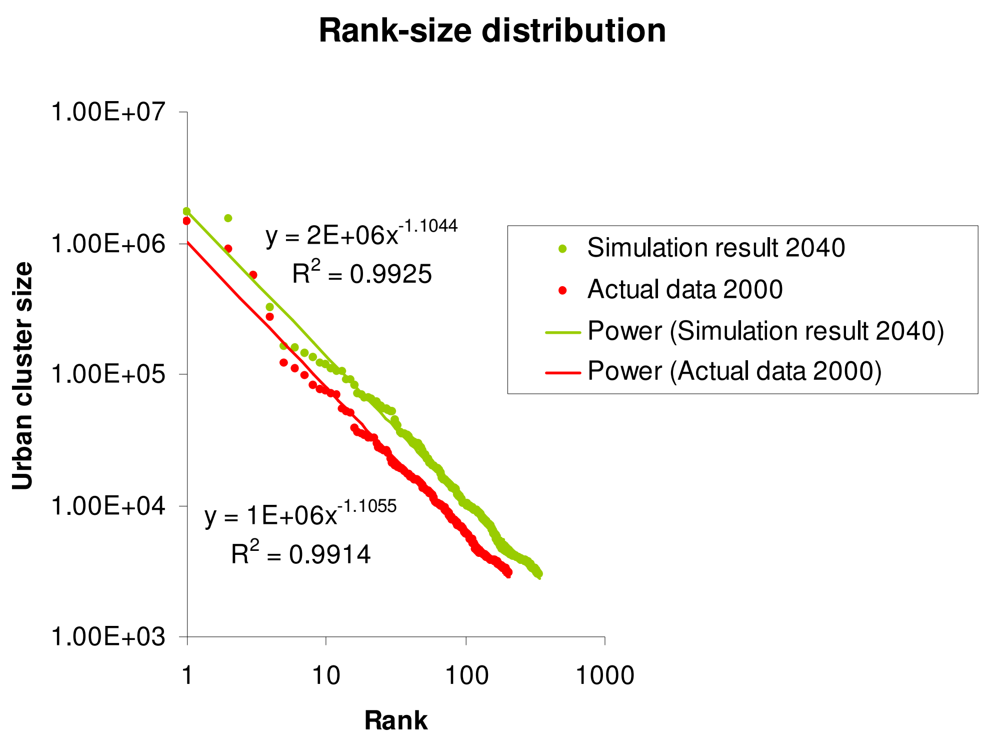

Figure 3: *Rank-size distributions for the actual data in 2000 and simulated data for 2040.*

CONCLUSION AND DIRECTIONS FOR FURTHER RESEARCH

Preliminary results show that the activity-based model generates realistic urbanization patterns from real world data. Moreover these results are grown from the bottom up using spatial explicit information on population and land-uses. However, the amount of migration from rural to urban areas is subject to calibration. The results shown here are to test the effect qualitatively and might therefore be exaggerated. A more detailed calibration would require data for two points in time.

The activity based model is an extension to Metronamica in that it adds information about densities to the CA land use model. As Occam's razor dictates that a model should be "as simple as possible but no simpler", the addition of more detail to produce land-use maps in itself is not a benefit. However, the additional information allows for research on the causal relation of land-use change, especially where these causes are incremental and relate to the density, such as for urbanization. In addition, the quantitative information is very useful for integrated land-use studies that include the disturbance of natural habitats the travel demands, as both depend on the amount of activities and not on the presence of land uses as such.

The results presented in this paper are preliminary and mainly used to test the model on a real world application. In that light the tests also gave some hints on possible future developments. Some model improvements that we foresee are the adjustment of the algorithms to include discrete dynamics instead of continuous distributions. One expected improvement is the explicit expression of persistence. In the current model, all activities are effectively reallocated each time step, while in fact most people do not change their location of residence each year. Therefore the persistence of activities and the attraction of that same activity on a location are effectively represented by one and the same parameter, while it represents two distinct effects. One other direction is the adjustment of the land-use allocation to allow for more functional land-use types such as central business district or suburb instead of residential and commercial land use. Additionally we intend to implement the activity based model in integrated systems as well to indeed benefit from the possible linkages as described above.

Finally, while testing the model we found a lack of methods that allow for a quantitative assessment of model results. Although there exists a number of methods that assess the accuracy of categorical maps (Couto, 2003, Hagen-Zanker and Martens, 2008), no such methods are available for population density maps.

REFERENCES

Barrredo, J.I., Demichelli, L., Lavalle, C., Kasanko, M. and McCormick, N. (2004) Modelling future urban scenarios in developing countries: an application case study in Lagos, Nigeria. Environment and Planning B 32, pp. 65 – 84.

Brown D.G., Page, S., Riolo, R., Zellner, M. and Rand, W. (2005) Path dependence and the validation of agent-based spatial models of land use. International Journal of Geographical Information Systems 19 (2): 153-174.

Cordoba, J-C. (2008) On the distribution of city sizes. Journal of Urban Economics 63, pp. 177-197.

Couto, P., 2003. Assessing the accuracy of spatial simulation models. Ecological modelling 167, pp. 181-198.

Davidson, W., Donnelly, R., Vovsha, P., Freedman, J., Ruegg, S., Hicks, J., Castiglione, J. and Picado, R. (2007) Synthesis of first practices and operational research approaches in activity-based travel demand modelling. Transportation Research Part A: Policy and Practice 41 (5), pp. 464-468.

Epstein, J.M. (1999) Agent based computational models and generative social science. Complexity 4 (5): 41 – 60.

Gallego J. & Peedell, S. (2001). Using CORINE land cover to map population density. In: European Environment Agency (2001). Towards agri-environmental indicators; Integrating statistical and administrative data with land cover information. EEA, Copenhagen, pp 92 - 104.

Hagen-Zanker, A. and Martens, P., 2008. Map comparison methods for comprehensive assessment of geosimulation models. In: Gervasi, O., Murgante, B., Lagana, A., Taniar, D., Mun, Y. and Gavrilova, M. (eds.) Lecture Notes in Computer Science, Proceedings of the 2008 International Conference on Computational Science and Its Applications ICCSA 2008, pp.194-209, Springer, Berlin, Germany.

Haines-Young, R. and Weber, J.L., (2006) Land accounts for Europe 1990-2000. EEA report 11/2006. European Environment Agency, Copenhagen.

Janssen, M. and Ostrom, E. (2006) Emperically based, agent based models. Ecology and Society 11 (2) 37.

Loibl W. and Tötzer, T., (2003) Modeling growth and densification processes in suburban regions – simulations of landscape transition with spatial agents. Environmental Modelling and Software 18, pp. 553 – 563.

Parker, D.C., Hessl, A. And Davis, S.C. (2008) Complexity, land-use modeling, and the human dimension: Fundamental challenges for mapping unknown outcome spaces. Geoforum 39: 789 – 84.

Robinson, D.T., Brown, D.G., Parker, D.C., Schreinemachers, P., Janssen, M.A., Huigens, M., Wittmer, H., Gotts, N., Promburom, P., Irwin, E., Berger, T., Gatzweiler, F. and Barnaud. C. (2007) Comparison of empirical methods for building agent-based models in land-use science. Journal of Land Use Science 2 (1), pp. 31 – 55.

RIKS (2009) Metronamica - Model descriptions. RIKS, Maastricht, The Netherlands.

Silva, E., and Clarke, K. C. (2002) Calibration of the SLEUTH urban growth model for Lisbon and Porto, Portugal. Computers, Environment and Urban Systems 26, pp. 525–552.

Van Vliet, J., Hurkens, J., White, R., and Van Delden, H. (Accepted) An activity based cellular automaton model to simulate land use changes. Accepted for publication in Environment and Planning B.

Veldkamp, A. and Lambin, A.F. (2001) Predicting land use changes. Agriculture, Ecosystems and Environment 85, pp. 1 – 6

Wu, F., and Webster, C.J. (2000) Simulating artificial cities in a GIS environment: urban growth under alternative regulation regimes. International Journal of Geographical Information Science 17 (7), pp. 625 – 648.

Yeh, A.G.O. and Li, X. (2002) A cellular automata model to simulate development density for urban planning. Environment and Planning B 29 (3), pp. 431 – 450.