THE INCORPORATION OF ACCESSIBILITY IN LAND USE TRANSITION POTENTIAL FOR CELLULAR AUTOMATA MODELS

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Abstract: Cellular automata (CA) models are used for simulating land use change for more than two decades. These models have a simple structure based on a cellular partition of space, considering a finite set of cell states (or land uses) and their interaction within a given neighborhood area, changing throughout time under a set of transition rules. Transition rules are based on more or less sophisticated measures of state transition: they can be more complex rules that try to incorporate the different drivers of land use change or they can be purely probabilistic rules that take into account only the states of neighboring cells. This last approach is often based on a measure of a transition potential that establishes a rank for state transition for every cell. There are many drivers of land use change and accessibility is acknowledged as being one of the most important ones. At the same time, transportation systems (thus accessibility) are also influenced by land use change. This suggests that CA models are potentially good tools to simulate these phenomena by considering the cross-interdependences between both. In this presentation, we make a reflection on how accessibility can be measured, incorporated, and used to improve CA transition rules based on transition potentials towards more representative models of land use change. We address not only modeling requirements but also the potential of using CA models to evaluate both the impacts of transportation policies in land use change, and vice versa.

Key words: Cellular automata, accessibility, urban change, policy testing.

1. Introduction

Cellular automata (CA) models are one of the most sophisticated tools to simulate any kind of phenomena of spatial nature. The mathematical concept introduced by Ulam and von Neumann in the 1940s was latter introduced to geography by Waldo Tobler (1979), starting a period of intensive theoretical development that gave birth to the first applications of CA to both theoretical instances and to real world case studies (Couclelis, 1985; 1987; White and Engelen, 1993; Batty and Xie, 1994). These theoretical foundations boosted numerous variations and improvements to geographic CA models that are now widely used for simulating increasingly more complex problems (Wu and Webster, 1998; Silva and Clarke, 2002; Barredo *et al.*, 2003; Liu *et al.*, 2008). The larger majority of these applications made use of regular cells derived from remote sense imagery and there is only a small group of studies that developed CA models considering irregular cellular fabrics (Semboloni, 2000; O'Sullivan, 2001; Pinto and Antunes, In press; Stevens *et al.*, 2007).

Accessibility has been classified as a major driver of urban growth for a long time and a significant number of the models developed to simulate urban growth incorporate accessibility and its interdependent effects with a series of other factors such as land price or household and activity location. A large majority of CA models also incorporate accessibility in their formulations, in particular considering it as one of the drivers that influence the system evolution through time (Santé *et al.*, 2010). Accessibility is included as one of the components in the formulation of transition rules, which play the role of engine that drives CA evolution. However, the majority of these models consider accessibility as a cell attribute, defined as the linear distance from a cell to the nearest road (and sometimes to rail or airport) infrastructure (Clarke *et al.*, 1997; Li and Yeh, 2000; Barredo *et al.*, 2003; He *et al.*, 2008; Yang *et al.*, 2008). This simple approach discards the effects that infrastructure capacity and travel demand has on the performance of the transportation system and their consequences on land use. Although it is not a matter for CA model to simulate the performance of transport systems, it is clearly possible to deepen the integration of land use simulation provided by the CA model with a more complex transport model that can provide a more elaborated measure of accessibility, which can include infrastructure capacity, travel demand, and multimodal systems.

This paper reports the application of our model within the research project called “Strategic Options for Integrating Transportation Innovations and Urban Revitalization (SOTUR)”[1]. We present the application of a CA model in which accessibility is a cell attribute calculated considering travel times over a real road network. Section 2 presents a description of our model with its basic formulation. In section 3 we present the results for the application of the model to simulate different scenarios considering the construction of an important urban road for the case study of Coimbra, Portugal. Finally, in section 4 we draw some comments on the use of accessibility in CA models and on the results of our model.

2. Model Description

The cellular automata model presented in this paper was designed to maintain the simplicity of the original concept. This section presents a brief overview about the different components of the model. For a detailed reading on this CA model and all its features see Pinto and Antunes (In press).

Cell is the first of the five key CA components. Our model uses irregular cells that aim to simulate real-world irregular spatial partitions, such as census blocks. Neighborhood, another key component of CA, is considered as a radial distance and it is a parameter calibrated by the model. The set of cell states, the next CA component, comprises six aggregate cell states (or land use classes): urban low density (UL) and urban high density (UH), which includes all the traditional land uses that are located inside urban areas, including public facilities and also public space; non-urbanized urban areas (XU) which are areas that could receive new urban developments; industry (I); non-urbanized industrial areas (XI); and areas where construction is highly restricted (R). Transition rules are another component of the CA model which play a key role as they represent the way the system evolves throughout the simulation. Our model uses a measure of state transition potential that is used for selecting which cells will change state at each simulation step. The potential function computes a calibrated value of accessibility, land use suitability, and neighborhood effect.

$$P_{i,s} = (v_P \times S_{i,s} + \chi_P \times A_i + \theta_P \times N_{i,s}) \times \xi, \forall i \in \mathbf{C}, s \in \mathbf{S}$$

where, for each cell i from the set of cells C, and for each state s from the set of states S, $P_{i,s}$ is the transition potential for state s of cell i, $S_{i,s}$ is the land use suitability value for state s of cell i, A_i is the accessibility value of cell i, $N_{i,s}$ is the neighborhood effect for state s of cell i considering its neighborhood V_i, v_P is the calibration parameter for land use suitability, χ_P is the calibration parameter for accessibility,

[1] This project is funded by the MIT-Portugal research program for transportation; for detailed information about the project access http://www.mitportugal.org/transportation-systems/sotur-strategic-options-for-integrating-transportation-innovations-and-urban-revitalization-overview.html.

θ_P is the calibration parameter for the neighborhood effect, and ξ is the stochastic parameter. Land use suitability is a binary value that has the value of 1 if a cell is suitable for a given land use and 0 otherwise, as defined by land use regulations in force. Accessibility is measured by a function of the travel time between cells (defined by their centroids) by the road network considering its hierarchical structure as follows:

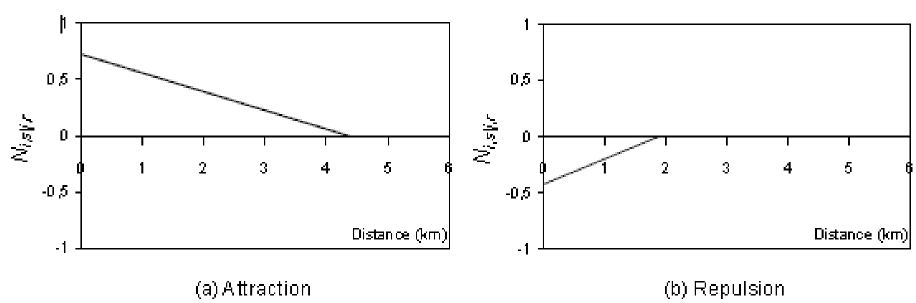
$$A_i = 1 - \frac{f\left(T_i^*\right)}{\left\| \sum_{j \in \mathbf{C}} f\left(T_j^*\right) \right\|}, \forall i \in \mathbf{C}$$

where $f(T^*_i)$ is an impedance function (typically an exponential function or a power function) of an aggregate measure of travel time given by

$$T^*_i = \alpha_A \times T_{i,C} + \beta_A \times T_{i,V} + \gamma_A \times T_{i,I}, \forall i \in \mathbf{C}$$

and $T_{i,C}$ is the travel time from cell *i* to the municipality's main town, $T_{i,V}$ is the travel time from cell *i* to its civil parish (or district) main village, $T_{i,I}$ is the travel time from cell *i* to the closest industrial site located in the municipality, and α_A, β_A, and γ_A are calibration parameters. The neighborhood effect simulates the spatial interaction between each pair of land uses. This interaction is modeled by a linear function that decays with distance until it is no longer observed. It has a normalized value and ranges from 0 if they not interact up to +1 if they attract each other (e.g. cell states UL and R, as depicted in Figure 1a) or from -1 if two land uses repulse each other (e.g. cell states I and UL, as depicted in Figure 1b) to 0 if they not interact. The neighborhood effect for a given cell is the sum of all the neighborhood interactions of this cell with all its neighboring cells within its own neighborhood, as defined by the neighborhood parameter.

Figure 1 Neighborhood effect interactions



Land use demand is proportional to the increase of population and employment, as well as to the variation of construction density. The assessment of model performance was made using contingency matrices and the corresponding *kappa* index (Couto, 2003). The comparison of the simulation map with the reference map through a measure of similarity is appropriate because it is oriented for the analysis of the entire territory as a distributed structure and not only as a centralized urban layout. But there are urban land uses (cell state R in the present classification) that were not considered in the changing dynamics. The consideration of the entire set of cell state for the calculation of the *kappa* index value would produce a distortion on its significance. To avoid this distortion, a modification of the *kappa* measure was considered, named k_{Mod}, accounting only the cell states that take part in the urban change dynamics. The calibration of the model was made through an optimization procedure called Particle Swarm with the goal of producing an extensive search of the set of calibration parameters that optimize the fitness function chosen for the model. This new type of optimization algorithm has given promising results for complex optimization problems. It is an optimization paradigm that simulates the movement of a group of individuals towards some goal, where the success of each individual influence its own searches and those of their peers (Kennedy, 1997). For an in depth reading about particle swarm see Parsopoulos and Vrahatis (2002).

The model was already applied to a group of different cases (Pinto *et al.*, 2009a; 2009b; Pinto and Antunes, In press) and proven to give good results in terms of the quality of the simulation, especially taking into account a comparison with other CA models that use *kappa* as performance measure reported in the literature (Santé *et al.*, 2010).

3. Model Application

The model was applied to a real world case study to simulate the impacts on urban growth of the construction of an important road ring in the urban area of Coimbra, Portugal. The main goal is to use this model application to exemplify the potential use of the model to scenario evaluation for planning purposes. The model was calibrated for a set of reference data that includes census data on demographics and employment for the years of 1991 and 2001, and considering the approved Municipal Master Plan legally in force. Two scenarios were designed, one baseline called “Baseline” which does not considers any change in the road network and another one considering the construction of the road ring called ‘Anel Pedrulha’, both taking into account the same values for population and employment growth rates.

3.1. Model calibration

The model was applied to study possible scenarios of urban growth for the city of Coimbra, in the *Centro* region of Portugal (Figure 2). Coimbra can be classified as a mid-size European city of 100 thousand inhabitants which plays the role of regional capital for the central area of Portugal due to the very high concentration of public administration, healthcare, and educational facilities of high hierarchical level. The city is the capital of a municipality of about 150 thousand inhabitants and heads a larger influence area of around 480 thousand inhabitants, the *Baixo Mondego* and *Pinhal Interior Norte* NUT3 regions.

The data was formatted into a specific dataset that complies with model requirements. This dataset uses statistical data obtained from both the national censuses of 1991 and 2001, provided by the Statistics Portugal, and data from the official statistics on employment provided by the Ministry of Labor and Social Security. In addition, land use was also derived from the municipal master plan in force updated considering the current occupation of the municipality. Cells were obtained from the intersection of the official census blocks from both 1991 and 2001 with the urban boundaries that are officially considered in the master plan. These cells combine urban form, derived from the urban boundaries, with reliable data from all the aforementioned statistical sources. Land use maps are depicted for the reference years of 1991 (Figure 3a) and of 2001 (Figure 3b).

Figure 2 Location of the municipality of Coimbra, Portugal

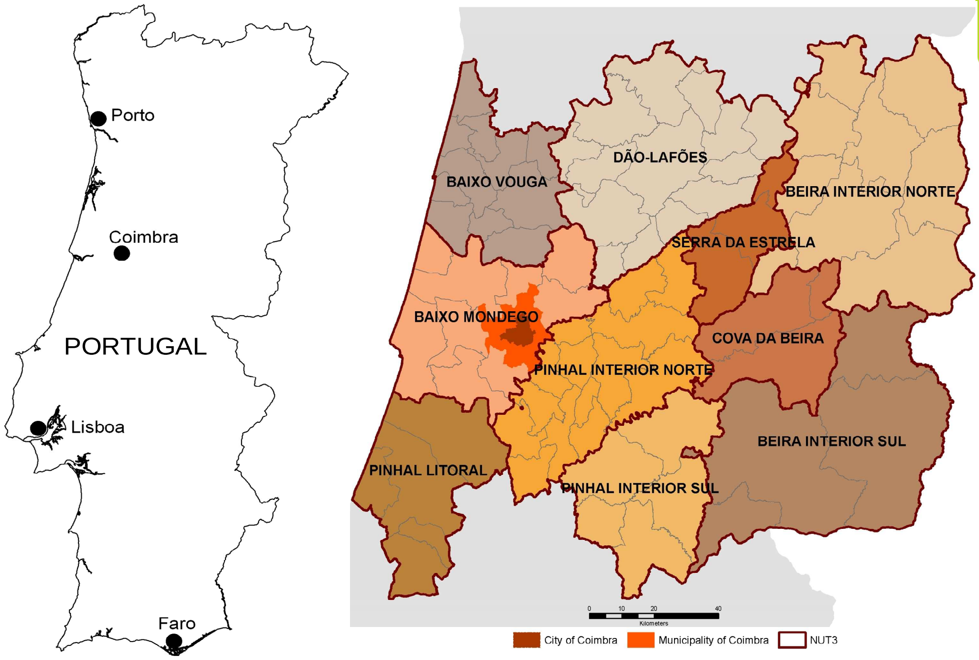
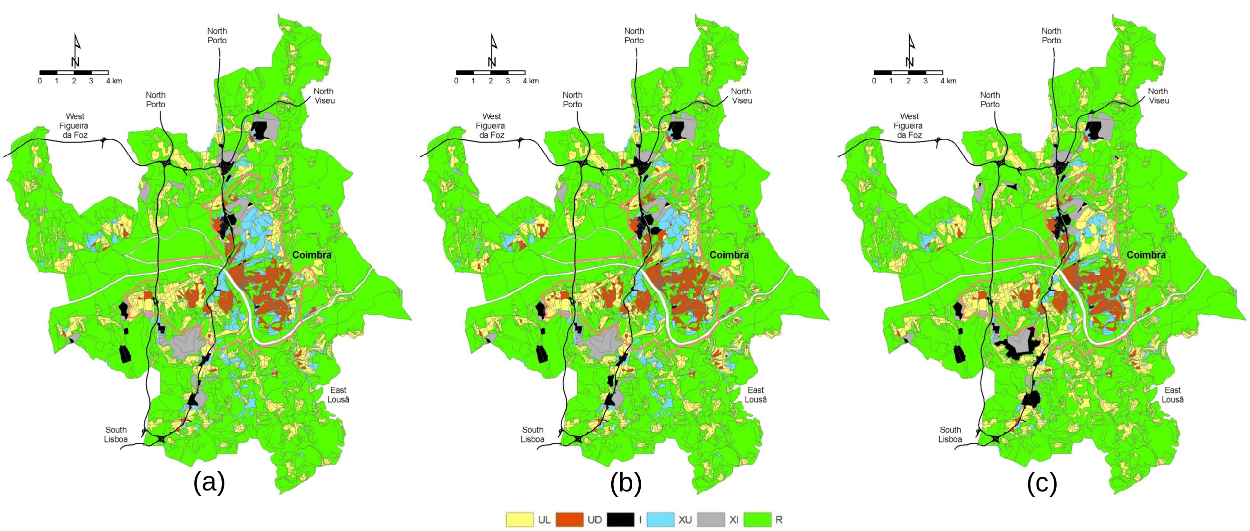


Figure 3 Land use maps for the municipality of Coimbra: (a) reference data for 1991, (b) reference data for 2001 and (c) simulation results for 2001



The model was calibrated using the reference datasets and it was able to achieve a value for k_{Mod} of 0,767 (for a *kappa* value of 0,876). The land use map for simulation results is depicted in Figure 3(c). This

k_{Mod} value represents a very good adjustment of the simulation to reality, considering the standard thresholds for the use of the *kappa* statistics commonly accepted in the literature. The value of the calibration parameter for accessibility in the potential function, χ_P was of 0,665, while the parameter for neighborhood effect, θ_P achieved the value of 0,841. The third parameter for land suitability, v_P only reached the value of 0,278. These values illustrate the importance of both accessibility and of the interactions between different land uses for land use dynamics.

3.2. Scenario design and evaluation

We designed two planning scenarios that would allow the evaluation of the impacts of building a new urban road ring in the northern area of the city. The two scenarios were designed considering a very simple pair of alternatives: (1) to build the “Anel da Pedrulha” road, enhancing accessibility for many origin-destination pairs; (2) to do nothing, maintaining the same road network and therefore the same accessibility conditions. The road maps for the two scenarios in 2021 are depicted in Figure 4(a) for the ‘Baseline’ scenario and in Figure 4(b) for the ‘Anel Pedrulha’ scenario. For both scenarios we established the same macro conditions in terms of population and employment growth, considering two periods of ten years that will coincide with the next two censuses (2001 to 2011 and then onwards to 2021), which are presented in Table 1. These values are in line with the most recent forecast for the population evolution for the next 50 years in Portugal. However, following the research option of creating optimistic scenarios for demonstration purposes, the growth rates are higher than the forecasted ones and employment growth was determined regardless of more recent trends in job creation.

Figure 4 Road network of the municipality of Coimbra in 2021 for (a) the ‘Baseline’ scenario and (b) for the ‘Anel Pedrulha’ scenario

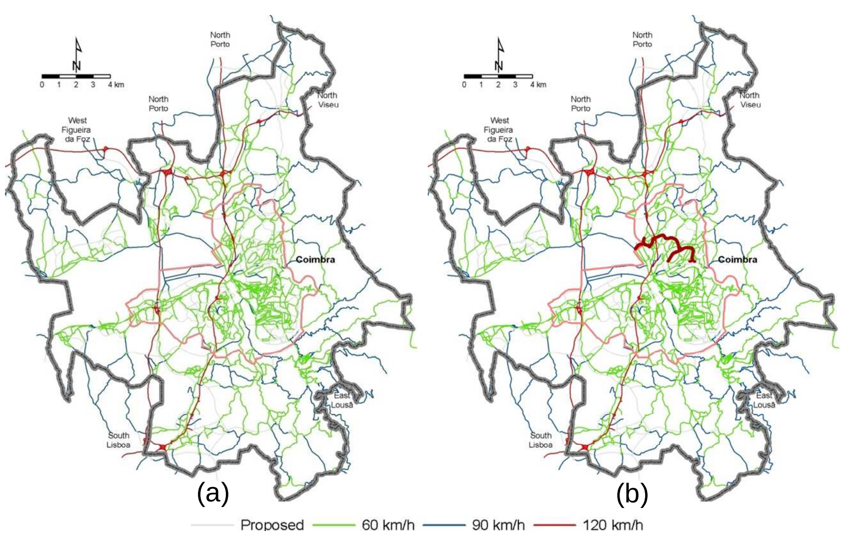


Table 1 Macro indicators for population and employment growth for both scenarios

	2001-2011	2011-2021
Population	+3%	+2%
Employment	+2%	+2%

Figure 5 Land use maps for the municipality of Coimbra, 'Baseline' scenario for (a) 2001, (b) 2011 and (c) 2021

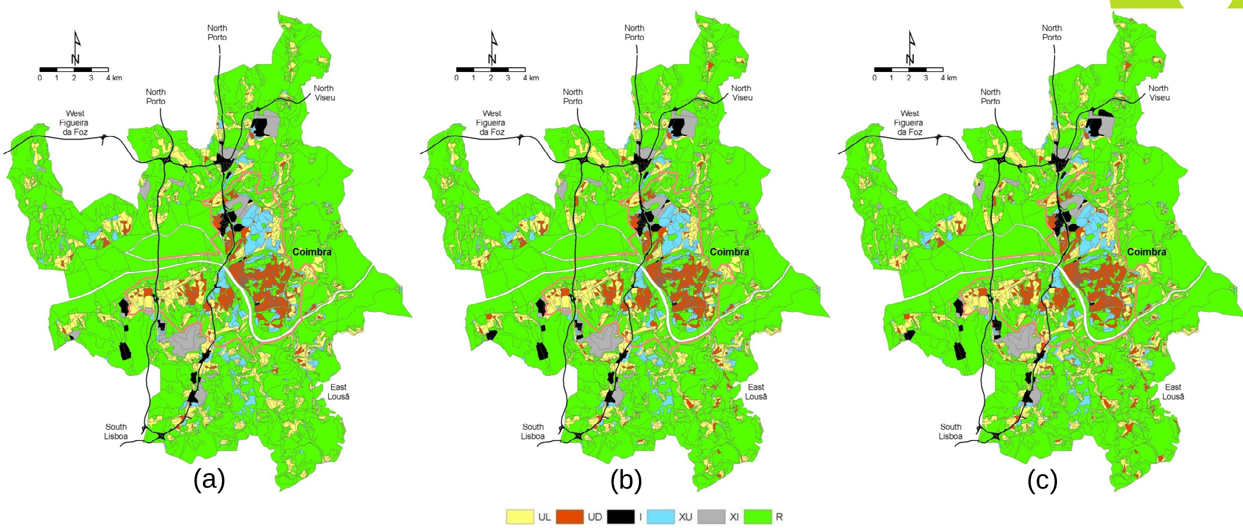
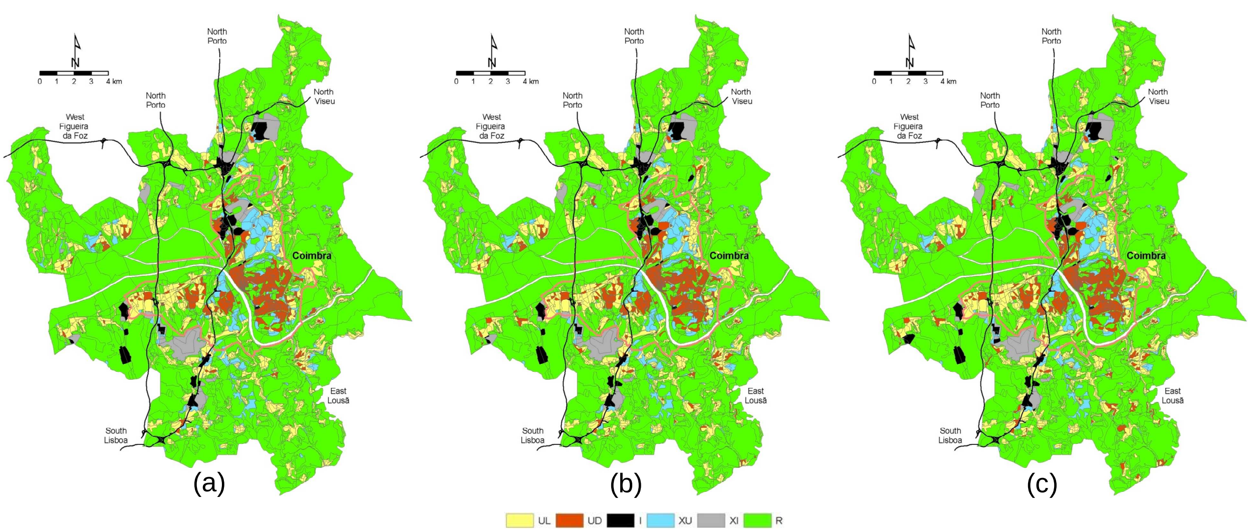
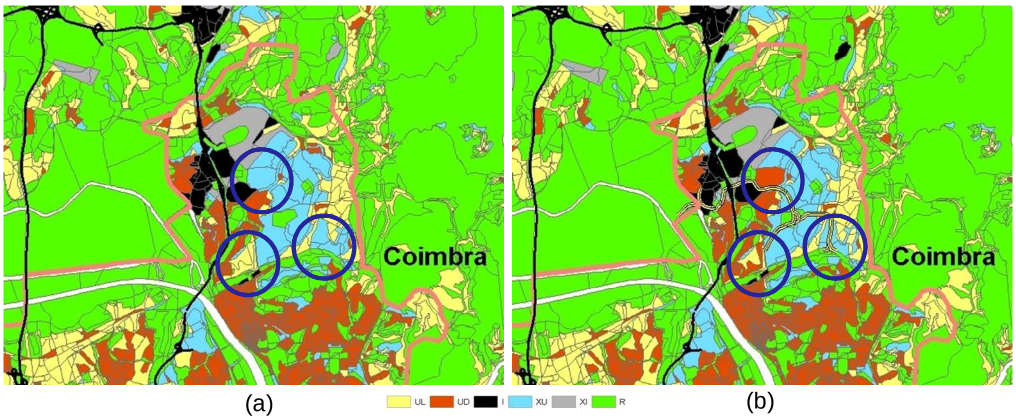


Figure 6 Land use maps for the municipality of Coimbra, 'Anel Pedrulha' scenario for (a) 2001, (b) 2011 and (c) 2021



We used the set of calibration parameters obtained from the calibration with reference data to run forecast analysis for both scenarios. Figure 5 depicts the land use maps for the 'Baseline' scenario for the two ten years period (reference situation in 2001 (a) and simulation results for both 2011 (b) and 2021 (2)). Likewise, Figure 6 depicts land use maps for the simulation of the 'Anel Pedrulha' scenario for the same years. An enhanced detail of the area directly served by the new road is depicted in Figure 7(a) for the 'Baseline' scenario and Figure 7(b) for the 'Anel Pedrulha' scenario. These results show that the impact of the construction of the ring is significant, as the attractiveness of cells directly served by the new road is much higher in the ‘Anel Pedrulha’ scenario, with more cells changing their state to more dense urban uses.

Figure 7 Comparison of the land use maps for the area directly served by the new road ring for (a) the ‘Baseline’ scenario and (b) the ‘Anel Pedrulha’ scenario



(a) (b)

4. Concluding Remarks

The model was applied to a real world case study to simulate the impacts on urban growth of the construction of an important road ring in the urban area of Coimbra, Portugal. The main goal of this application was to illustrate the possibilities of using this type of model approach to capture and forecast the complex land use and transport interactions. The scenarios designed for this application are quite simple but they were useful to exemplify what types of simple analysis are possible to be made in order to support a discussion over different planning choices. These results were presented in a meeting that included different officials from the administration – including the Mayor of Coimbra and several representatives of national agencies with competences in spatial and transportation planning – who engaged in a preliminary discussion over its results, which illustrates the potential of its use as a decision support tool. There is a great potential in using more complex transport models to provide better accessibility indicators to CA models. First, with the use of transport models accessibility is no longer just an exogenous input. Second, it is possible to relate land use parameters with transport parameters, testing different settings for their values in order to evaluate their interdependencies. This provides more robust tools to simulate the complexity of land use and transport interactions, enhancing the possibilities of performing policy testing to the combination of planning and transport policies and programs. We are now incorporating new features to the accessibility model, namely the possibility of considering multimodality and the introduction of different scales of analysis.

Bibliography

Barredo, J., M. Kasanko, N. McCormick & C. Lavalle (2003) Modelling dynamic spatial processes: simulation of urban future scenarios through cellular automata. Landscape and Urban Planning, 64(3), 145-160

Batty, M. & Y. Xie (1994) From cells to cities. Environment & Planning B: Planning & Design, 21(Celebration Issue), 531-548

Clarke, K., S. Hoppen & L. Gaydos (1997) A self-modifying cellular automaton model of historical urbanization in the San Francisco Bay area. Environment and Planning B: Planning and Design, 24(2), 247-261

Couclelis, H. (1985) Cellular worlds - a framework for modeling micro-macro dynamics. Environment and Planning A, 17(5), 585-596

Couclelis, H. (1987) Cellular-dynamics - how individual decisions lead to global urban change. European Journal of Operational Research, 30(3), 344-346

Couto, P. (2003) Assessing the accuracy of spatial simulation models. Ecological Modelling, 167(1-2), 181–198

He, C., N. Okada, Q. Zhang, P. Shi & J. Li (2008) Modelling dynamic urban expansion processes incorporating a potential model with cellular automata. Landscape and Urban Planning, 86(1), 79-91

Kennedy, J. (1997) The particle swarm: Social adaptation of knowledge. Proceedings of the 1997 IEEE International Conference on Evolutionary Computation (ICEC '97). Indianapolis, IN

Li, X. & A. G. O. Yeh (2000) Modelling sustainable urban development by the integration of constrained cellular automata and GIS. International Journal of Geographical Information Science, 14(2), 131-152

Liu, X., X. Li, X. Shi, S. Wu & T. Liu (2008) Simulating complex urban development using kernel-based non-linear cellular automata. Ecological Modelling, 211(1-2), 169-181

O'Sullivan, D. (2001) Exploring spatial process dynamics using irregular cellular automaton models. Geographical Analysis, 33(1), 1-18

Parsopoulos, K. E. & M. N. Vrahatis (2002) Recent approaches to global optimization problems through Particle Swarm Optimization. Natural Computing, 1235–306

Pinto, N. & A. Antunes (In press) A cellular automata model based on irregular cells: Application to small urban areas. Environment and Planning B: Planning and Design

Pinto, N., A. Antunes & J. Roca (2009a) Application of a cellular automata model to the Metropolitan Area of Barcelona In ROCA, J. & R. BIERE-ARENAS (Eds.) Proceedings of the 5th International conference on Virtual Cities and Territories. Barcelona, Spain, Center for Land Policy and Valuation

Pinto, N., A. Antunes, J. Roca (2009b) Cellular Automata in Urban Simulation: Basic Notions and Recent Developments", In BAVAUD, F. and C. MAGER, Handbook on Theoretical Quantitative Geography, FGSE, University of Lausanne, Lausanne, Switzerland, pp 365-402,

Santé, I., A. M. García, D. Miranda & R. Crecente (2010) Cellular automata models for the simulation of real-world urban processes: A review and analysis. Landscape and Urban Planning, 96(2), 108-122

Semboloni, F. (2000) The growth of an urban cluster into a dynamic self-modifying spatial pattern. Environment and Planning B: Planning and Design, 27(4), 549-564

Silva, E. & K. C. Clarke (2002) Calibration of the SLEUTH urban growth model for Lisbon and Porto, Portugal. Computers, Environment and Urban Systems, 26(6), 525-552

Stevens, D., S. Dragicevic & K. Rothley (2007) iCity: A GIS-CA modelling tool for urban planning and decision making. Environmental Modelling & Software, 22(6), 761-773

Tobler, W. (1979) Cellular geography. IN GALE, S. & G. OLSSON (Eds.) Philosophy in Geography. Boston, D. Reidel

White, R. & G. Engelen (1993) Cellular automata and fractal urban form: a cellular modelling approach to the evolution of urban land-use patterns. Environment and Planning A, 25(8), 1175-1199

Wu, F. & C. J. Webster (1998) Simulation of land development through the integration of cellular automata and multicriteria evaluation. Environment and Planning B: Planning and Design, 25(1), 103-126

Yang, Q., X. Li & X. Shi (2008) Cellular automata for simulating land use changes based on support vector machines. Computers & Geosciences, 34(6), 592-602