

Modelling urban expansion spatial patterns: a methodological approach using cellular automata

João Xavier, joaomvxavier@gmail.com

MSc in Territorial Engineering , Instituto Superior Técnico, Universidade de Lisboa

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ABSTRACT

This work addresses urban sprawl modelling using tools integrated within a GIS (Geographic Information System). In it, a modelling of spatial patterns of urban expansion is performed following a methodological essay with CA.

A set of references focusing major European projects and studies on urban sprawl was revised and the main characteristics were synthesized. Based on these studies, an approach was decided in terms of modelling the urban dynamics in land use changes based on scenarios.

After identifying CA (Cellular Automata) as models for the dynamics of the land use change phenomenon, three widely used CA types – MOLAND/METRONAMICA, Sleuth and CLUE-S – were described and compared, in order to evaluate their adaptability to specific modelling scenarios.

The work includes the development of an operational tool capable of producing output maps illustrating the dynamics of land use. The tool might encourage a more informed discussion of scenario impacts between agents with responsibility in territorial planning and management and/or the stakeholders involved in such discussions.

The case study was the Setubal Peninsula (the southern part of Lisbon's Metropolitan Area), where distinct periurban area types were identified on the ongoing PERIURBAN project. Using a series of land cover datasets, essays on the usability of the tool were conducted, by applying it to former dates for which land use changes were known. The tool was then applied in a scenario-based essay to foster future discussions within PERIURBAN project.

Keywords: Urban Sprawl, Land Use Dynamics, Lisbon Metropolitan Area, Cellular Automata (CA), Scenarios, Periurban areas.

INTRODUCTION

Managing urban population change will be one of the most important challenges during the next decades, along with moderating the impacts of climate change. In developed countries, the urban future will involve dealing with complex changes in the composition of urban populations and containing urban sprawl beyond the suburbs to retain the critical ecosystem services that will sustain population growth. (Plurel, 2010, p.20).

Exploring future perspectives concerning planning strategies development it's an hard task due to uncertainties regarding the conditions that are inherent to it. Hence, scenario techniques use assumes a prominent role to fundament discussion about policies impacts on the future.

Scenarios are not predictions or preferences of the future. Instead, the main idea of the scenario approach is to use multiple perspectives to explore a specific problem (Rounsevell *et al.*, 2005, p.118).

Despite its qualitative nature, scenarios can aswell resort or be themselves resorted to models applicability or other quantitative analysis that can: i) be used to illustrate or testing scenarios, ii) to "feed" the construction of scenarios. For example, scenarios from the European Environmental Agency's PRELUDE project (EEA, 2007) take land use models to simulate potential impact of each scenario in land use transformation.

Thus, the objectives of this work are to understand the approaches and perspectives in the literature with regard to modelling strategies of the land use change of peri-urban areas, and to develop an operational tool that allows, depending on parameters chosen by an analyst, to produce maps which illustrate the dynamics of land use for specific moments. The conjugation of these goals will supportively foster a more informed discussion between agents with responsibility for planning and managing the territory.

In order to frame the object of the study, and according to the motivations in achieving the objective, the following methodological steps are taken:

- **Literature review:** to expose and systematize the approaches and perspectives in the literature with regard to modelling strategies of peri-urban areas development;
- **Methodological approach:** based on the principles of generic urban expansion modelling tools, and with the knowledge from the previous step in synthesizing the major aspects of land use change in peri-urban areas, the goal is to develop an operational solution to model it in perspective;
- **Validation and calibration:** using a series of land cover datasets in a case study, essays on the usability of the tool may be conducted through the application to previous dates, on which land use changes are known.
- **Construction of a scenario-based essay:** application of the tool in a scenario-based essay to foster future discussions within the PERIURBAN project for a case study (the Setúbal Peninsula - southern part of Lisbon's Metropolitan Area - was the selected site).

THEORETICAL FRAMEWORK

A city can be seen as a self-organizing system open and complex, distant from balance and that lives in a constant Exchange of goods and energy with other cities and parts of itself (Yan Liu, 2009). Urban development is therefore a spatially dynamic process that displays entities of a self-organizing system.

Like the spreading of a disease or a fire, urban areas boundaries are in constant expansion in the direction of nearby rural areas. Hence, past urban configuration has a major influence in the future urban patterns. This idea suggests that the perspective over self-organization paradigm to explain the local behaviour it's the more realistic one for urban development modelling, resulting in the emergence of a new group of models, where geosimulation thought automata belongs (Benenson e Torrens 2004; Wu 1998a; Batty 1997, 1995; White e Engelen, 1994, 1993; Couclelis, 1985, cit. Liu, 2009, p.17).

A **cellular automaton** (CA) is a discrete mathematical model especially suitable for the representation of spatial evolutionary processes, because of its characteristics: (i) the representation of space, arranged in a spatial fabric composed of a network or regular tessellation by cells (ii), capacity of simulating development and transformation of values associated to the tessellation, because information is processed and propagated through a cell's neighbourhood. A cellular automaton is thus a dynamic spatial system: each cell is associated, at each instant, to a value that characterizes it and can be described as "state". The state of a cell in the array depends on the previous state of the cells in its neighbourhood, according to a set of defined transition rules (Liu, 2009).

A conventional cellular automata is based on 5 elements:

- **Euclidean space** – space divided into a matrix of identical cells;
- **Cell neighbourhood** – for each cell it is necessary to indicate its neighbourhood. E.g.: in diffusion processes 4 (Von Neumann) or 8 (Moore) cells compose a neighbourhood;
- **State** – representing associated characteristics of a cell set in a given time;
- **Transition rules** – determines the state of each cell according to the state of cells in its neighbourhood in previous time steps;
- Discrete variable **time steps** – iterations in which modelling process takes place.

Mathematical representation of a conventional cellular automaton can be explained according to:

$$S_{X_{ij}}^{t+1} = f\left(S_{X_{ij}}^t, S_{\Omega_{ij}}^t\right)$$

Where $S_{X_{ij}}^{t+1}$ represents the state of cell X_{ij} at a time $t+1$ and f is a function representing transition rules at previous time t , applied on cell X_{ij} and also over a set of cells in its neighbourhood, and can be expressed in a verbal form that illustrates a generic principle of the development of a cellular automaton, namely:

IF something happens in the neighbourhood of a cell;
THEN something else will happen to the cell at the following time step.

After identifying CA as models for the dynamics of the land use change phenomenon, three widely used CA types – MOLAND/METRONAMICA, Sleuth and CLUE-S – were described and compared, in order to evaluate their adaptability to specific modelling scenarios.

METRONAMICA/MOLAND is a land use model based in CA developed by RIKS (Research Institute for Knowledge Systems).

METRONAMICA/MOLAND applies the basic principles of CA extending these basic principles to 3 characteristics that differentiate it from the more conventional models: (i) the weighting functions based on the distance between cells, (ii) integration with GIS and (iii) restricted cell transition.

The transition rules work by changing each cell to the state whose potential is greater, conditioned by the number of cells in each state have to be equal to land use demand for each state generated in each iteration. The demand for a certain land use (area to be changed) is generated outside the CA during each iteration, and the cells are prioritized by the potential transition beginning to change states that have the greatest potential in a decreasing order until the number of altered cells corresponds the demand for each land use area generated. Each cell is covered by this algorithm in each iteration. Extern to the CA model, at a global scale, the model uses economic growth, demographic and environmental data. This information is often extracted from scenarios prepared by planning agencies, developers, scientific panels, etc.. Through these data global population growth and economic activity by sector is estimated and included in the model as trend lines (functions or trends). The model then calculates the growth of the system and defines the interconnection of sectoral growth with land use. The growth will not be distributed evenly across the modelled area, and regional inequalities will influence the allocation of new land use cells through spatial interaction dynamics - gravitational dynamic model.

The **Sleuth** model was originally developed by Keith Clark (University of California) in the early 1990s on the cooperation between US Geological Survey (USGS) with Environmental Protection Agency (EPA).

SLEUTH defines four types of growth rule which occur sequentially and iteratively: **spontaneous growth, new spreading centres, edge growth, and road-influenced growth**. A set of four growth types forms one growth cycle which represents one year in the simulation environment. In addition to the growth rules and coefficients that invoke and control urban growth, another rule set “kicks” in to complete the urban growth dynamics of SLEUTH. While the five coefficients are defined as model parameters at the beginning of the simulation, the **self modification rules** at the global scale dynamically alter certain coefficients during the simulation runs. What this does is to speed up or slow down overall urban growth (Kim *et al.*, 2011).

The original idea for the model **CLUE** was developed by Tom Veldkamp and Fresco Louise, published in 1996.

CLUE-S (the Conversion of Land Use and its Effects at Small regional extent) is sub-divided into two distinct modules, namely a non-spatial demand module and a spatially explicit allocation procedure. The relations between land use and its driving factors are thereafter evaluated using stepwise logistic

regression (Verburg et al, 2002, p.396). For the land-use demand module, different alternative model specifications are possible, ranging from simple trend extrapolations to complex economic models. The choice for a specific model is very much dependent on the nature of the most important land-use conversions taking place within the study area and the scenarios that need to be considered. Therefore, the demand calculations will differ between applications and scenarios and need to be decided by the user for the specific situation. The results from the demand module need to specify, on a yearly basis, the area covered by the different land-use types, which is a direct input for the allocation module (Verburg et al, 2002, p.395).

METHODOLOGY

For developing a urban land use modelling application was chosen to use a GIS software (ArcGIS 9.3) software and spreadsheets (Excel) that allows the management of information and computation over matrixes , programming in an accessible and intuitive language (a macro in VBA).

The urban land use modelling application developed uses raster matrixes with geographic data representing the factors considered to influence the dynamic of urban land use over the analyses years.

The application uses matrixes interaction to determine the transition to urban land use probability in each cell of a land use map, by assessing several factors and synthesizing it into the equation:

$$P = \sum_{i=1}^5 x_i \times p_i$$

, where: (i): x_i is the weight of each factor; (ii) p_1 is a random number between 0 and 1 generated by the application; (iii) p_2 is a transition to urban land use probability according to the centrality potential representing attraction to urban clusters; (iv) p_3 is transition to urban land use probability according to road proximity;(v) p_4 is the transition to urban land use probability according to land use in actual time step; (vi) p_5 is transition to urban land use probability according to the amount of urban cells actually existing in the neighbourhood (Moore neighbourhood of the 8 closest cells).

Thus, it is intended to reach a function of total transition probability that is calculated in an additive and not multiplicative method, because that way any factor equal to 0 would cause the overall 0 value, although not all factors are mutually exclusive. In the equation of probability only the factor P (existing land use) is eliminatory and that problem is solved in the form of a condition "IF" the land use to changeable to urban "THEN" the total probability is 0. p_2 and p_3 are calculated considering a designated number of equal ranges to each is assigned a certain probability value, inserted in an array. The application finds the position of the array from which should retrieve the probability value according to: $Integer \left[\left(\frac{Value \ X_{i,j}}{MAX} \right) \times Number \ of \ ranges \right]$. p_5 is obtained by counting urban cells in the neighbourhood of a cell and accordingly designating a probability value.

The whole procedure is repeated until all cells are assessed and a full probability matrix of the same size as input data is filled for each time step considered. Finally, based on the amount of cells to change for urban occupation defined by the user (externally to the model) the application seeks the highest probability values, changing the state of those cells to urban land use. Afterwards procedure is repeated for every year (time step) considered. The resulting grid of land use can then be imported into GIS software as an ASCII text file.

CALIBRATION AND VALIDATION

Calibration is “the estimation and adjustment of the model parameters and constraints to improve the agreement between model output and a data set”, whereas validation is “a demonstration that a model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model” (Rykiel, 1996, cit. Pontius *et al.*, 2004, p.447).

To run the model, datasets for land use (Corine Land Cover 2000 and Corine Land Cover 2006), roads, Peri-Urban Tipologies (Peri-Urban Cluster units) and a Centrality potential map were used, the last two obtained through project PERIURBAN (“Peri-urban areas facing sustainability challenges: scenario development in the Metropolitan Area of Lisbon”) team.

The probabilities and urban land use demand, to be inserted as an input of the model, were extracted from the analyzed land use datasets concerning the time period 2000-2006. It was possible to find the cells whose land use changed and summarize this information by centrality potential, roads distance and land use. Conditional probabilities (given the change for urban land use has occurred) were calculated (Erro! A origem da referência não foi encontrada.). Probabilities according to urban neighbourhood of a cell were arbitrated to emphasize the intended pattern of urban patch boundary attraction (0,05 if 0; 0,1 if 1; 0,15 if 2 and 0,7 if more than 3).

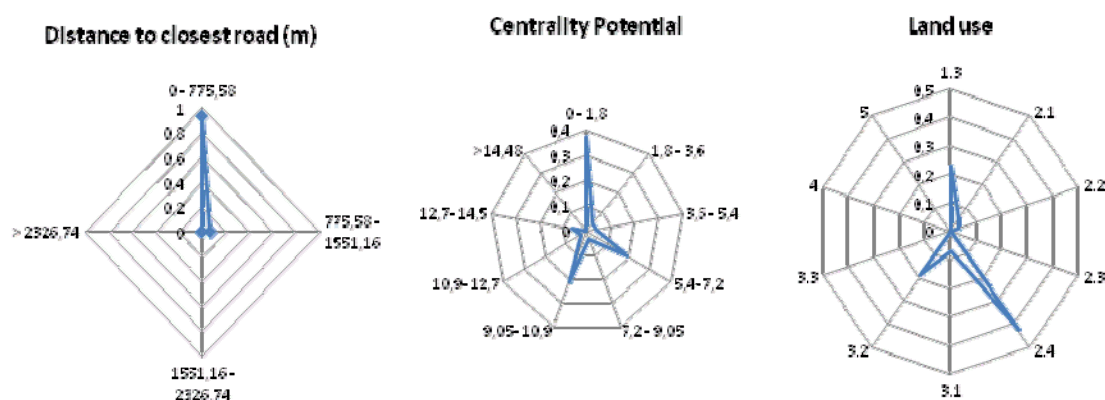


Figure 1 - Transition to urban land use probabilities (2000-2006)

For the period 2000-2006, the application classified the output urban land use cells in three categories: (i) correct location, (ii) false positive – urban cells generated in wrong locations, and (iii) false negative – location where urban cells should be generated but weren’t. To assess the distribution patterns of the generated urban cells a Global Error was calculated, weighted by each peri-urban typology unit.

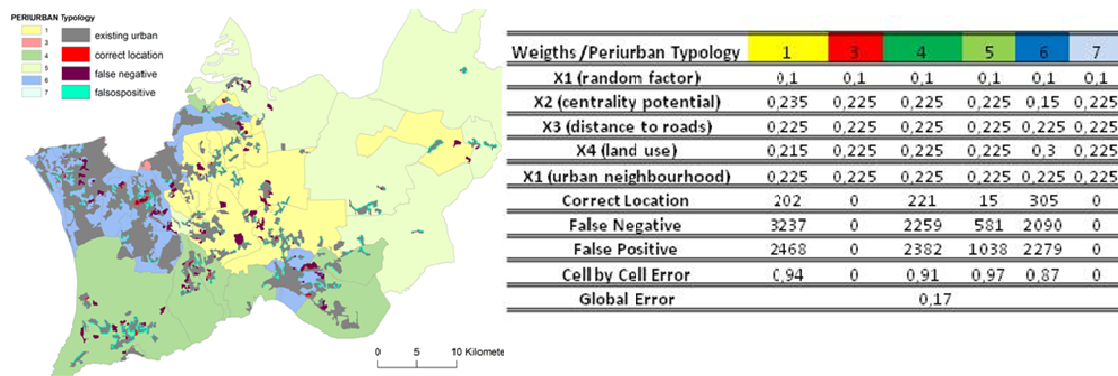


Figure 2 - Output map and evaluation parameters (2000-2006)

Using the parameters (probabilities) referred before it was possible to achieve an 83% global precision performance output (Figure 2). The global patterns of urban cells distribution over the territory was well simulated using the parameter weights indicated in the table above.

SCENARIO BASED ESSAY

In this chapter the modelling application developed for this study was tested in a scenarios based essay – chosen from scenarios proposed by the Periurban project expert's team - with the consequent variation of the parameters. In this exercise the choice was to analyze one scenario representing the perspective of a global action/influence level centred on individual interest (private).

The scenario discussed afterwards displays a society whose policies are regulated by a Global framework privileging the individual interest (private), presenting a society that is exposed to the more favourable or unfavourable impacts of globalized borders, markets and information.

Accordingly, this scenario points to a strong social disruption on one hand and, on the other hand, a reduction of the government control over the territory. Presumably this would result in significant changes over urban land use, particularly over high natural value areas that present characteristics for tourism and luxury housing - seasonal (holiday) or permanent - for seniors and domestic or foreign tourists. This process is justified according to a strong deregulation, favoring construction of luxury condos and low density hotel units. The coastal zone (located in the area of typology 4) is perhaps the main location that suffers urban pressure in the study area.

Population would suffer a significant reduction in their purchasing power; the demand for housing for average citizen would be fundamentally driven by unqualified foreign immigration. This population tends to seek the periphery of urban centres, where the price of housing would be lower, and where they still would have access to the central area by the still existing public transportation.

An adjustment of the model parameters was performed to simulate these conditions: To represent the increase in the transition to urban land probability in the coastal belt of peri-urban Typology 4 was necessary to create a map of distance to the coastline in raster format – representing attraction to

places with a ocean view and access - where each cell displays the value of the closest distance to the ocean. The distance to roads factor, unlike what was done in the calibration of the model for the period 2000-2006, wasn't considered as relevant. For this scenario time horizon starting in 2006 to 2025, all parameters were arbitrated to privilege attraction to coast line in a particular area and to significant urban centres in the remaining of the study area (Figure 3).

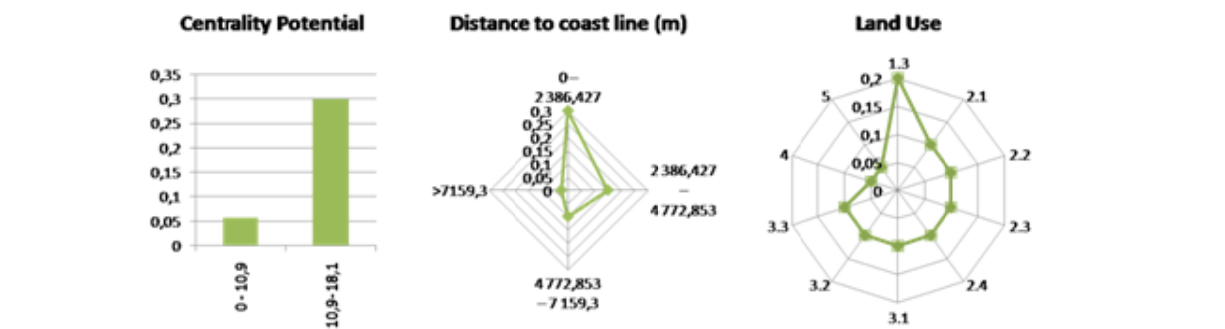


Figure 3 - Transition to urban land use probabilities (scenario)

Due to the unavailability of urban land demand data for the LMA (Lisbon Metropolitan Area) , was used a forecast for construction (source: ICT / AECOPS , 2011) , considering the most optimistic scenario in the report. It should be noted that this evolution for the construction sector refers to a nationwide frame and includes remodelling and public construction works. This information indicates an average annual growth rate of -5.60% for period 2005-2010, , 0.3% for the period 2010 to 2015, 3,6% for the period 2015 to 2020 and 2.20% for 2020 to 2025. This variation rates are reflected on an urban land use change of 25 219 cells, about 6 301 ha. Applying the referred probabilities and land use demand to the model, generated the following output with the parameters weight displayed. The model indeed responded to inputs as would be predicted by allocating the majority of cells generated in a dispersed form (representing the low density) along coastline in typology 4 areas and distributing the rest along the major urban centres boundaries.

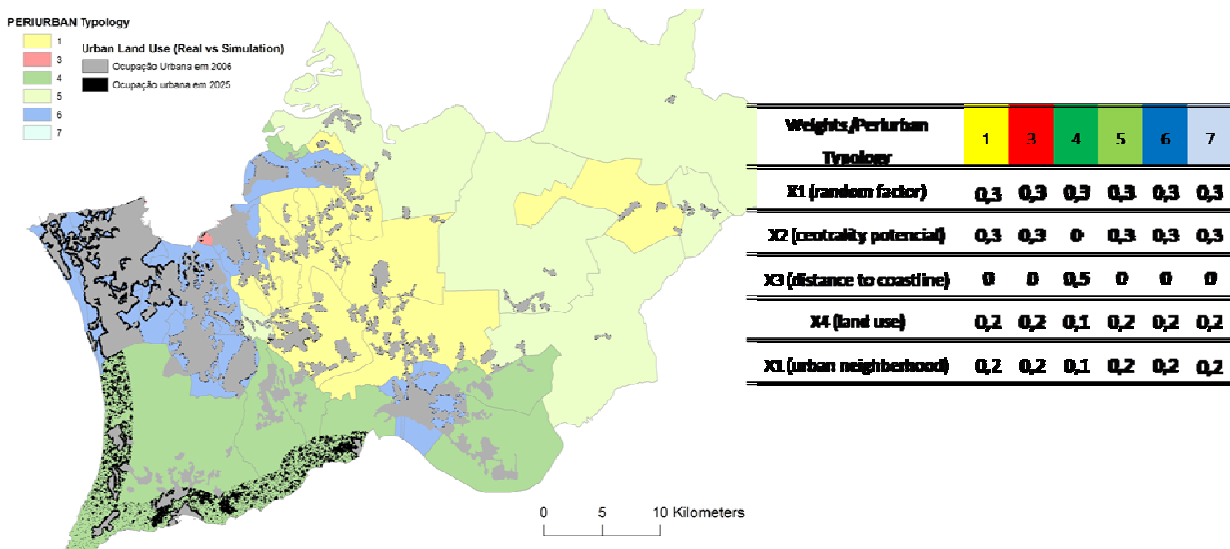


Figure 4 - Output map and parameters weights (scenario)

CONCLUDING REMARKS

The general perception of the literature review is that the understanding of the urban sprawl phenomenon is essential for implementing policies to sustain population's quality of life and ecosystems that support it.

Considering that the urban sprawl is usually an irreversible phenomenon, it becomes evident the need to plan, hence is necessary to have tools that help to sustain the discussion about causes and effects of policies and their impacts on the future of the territory and its dynamics.

After the general principles of the studied models were analyzed, their most positive and negative aspects, it was proposed to develop an application to model and produce maps on the dynamics of land use at a sub-regional level according to some parameters and factors which were considered as having influence. This application should be an operational solution for modelling the transition from several land use types to urban, based on cellular automata and able to transpose it to maps in raster format, through the interaction of multiple data sets. The application identifies, based on these factors, the cells - the most basic units of the territory represented in a grid - that have the highest probability of changing its land use to urban. Afterwards, using the number of cells that change its land use (demand for urban land use obtained externally to the model), the application proceeds to changing the land use for this amount of cells, following a hierarchy depending on the value of the probability for urban land transition.

The application was tested and validated using spatial data from time periods in which the transition of land use was known. Based on information from the PERIURBAN project was possible to characterise the study area - through its division into typological peri-urban make the application respond differently depending on the territorial division by this characterization

The model was able to respond to the carried out tests in an adequate way, simulating some of the growth patterns detected and distributing the new urban areas consistently over the study area, and thus replicating the patterns that occurred in reality. Although, the accuracy of the model at the location on a cell by cell basis was not fully achieved, mainly because the distribution of transition probabilities over the territory should have been more segmented and heterogeneous, resulting in more exclusive probabilities ranges.

It was possible to model quite well the more empirical understanding of phenomena such as urban sprawl across the boundaries of pre-existing urban patches and attractiveness to roads, as a structural element of urban sprawl. The application simulated in a less satisfactory way the generation of new urban settlement and its expansion, which suggests that more factors – e.g.: biophysical factors such as terrain slope - should be considered in future trials, in order to better capture the complexity of dynamic land use changes.

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