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# Complexity, Emergence and Cellular Urban Models: Lessons Learned from Applying Sleuth to Two Portuguese Metropolitan Areas

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**ABSTRACT** *We explore the simulation of urban growth using complex systems theory and cellular automata (CA). The SLEUTH urban CA model was applied to two different metropolitan areas in Portugal, with the purposes of allowing a comparative analysis, of using the past to understand the dynamics of the regions under study, and of learning how to adapt the model to local characteristics in the simulation of future scenarios. Analysis of the two case studies show the importance of SLEUTH's self-modification rules in creating emergent urban forms. This behavior can help build an understanding of urban social systems through this class of CA.*

## Introduction

The concentration of population in urban areas and accompanying rapid urban growth is a global phenomenon. One would imagine, therefore, that these problems have less magnitude where population growth is stable, or even in decline: as is the case in Portugal. Despite a long period of growth at about the 1% rate during most of the twentieth century, and a boost when some 5-800,000 people returned from the colonies after the 1974 revolution, the country's population is likely to peak some time in this decade at about 10.8 million, and then will decline. Yet ironically, urban growth is rampant in Portugal, centered in the two largest cities of Lisbon and Porto. Urbanization is obviously not simply a linear function of population growth, the decline in household size and the

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ageing of the population imply a far more subtle dynamic. Traditional modelling approaches based solely on demographic trends seem to fail to account for contemporary urban growth. Therefore, it is important to take into account urban growth through time, and particularly, its recent evolution, collective social preferences for different styles of living, and recent market trends. These elements have a key impact on how urban land uses are organized. Urban modelling approaches that are sensitive to local diversity in these factors can be more successful when simulating various shapes, intensities and velocities of urban growth throughout space.

Understanding such non-linear and negative feedbacks requires a complex systems approach in order to better understand the processes involved and to help assure that future urban forms are both suitable living places and are environmentally sustainable. Until recently, complexity was generally associated with randomness, and science's primary objective was to reduce this randomness and reveal the order, either by inferential statistics or by the construction of analytic models. Yet a consequence of such reduction methods was the loss of the local detail that could help us to understand the interconnectedness of urban systems.

Complexity theory has become important to understand self-organized, critical and chaotic kind of systems (Wilson, 2000; Phillips, 1999; Kay, 1999; Toffoli, 1998; Holland, 1995; White, 1994; Kauffman, 1993; Prigogine, 1984). Complexity in nature is often the result of continuous adaptations to change. The tools for understanding urban landscapes are inherently static and many of the feedbacks are unknown, or unquantifiable. The consequence is that our design and planning solutions often lack the ability to respond to change and to integrate with the rest of the environment (Itami, 1988: 52). From early origins in physics and biology, particularly in the field of Artificial Life (Delorme, 1999; Goles, 1996; Resnick, 1995; Langton, 1991), complexity theory has grown to influence many sciences, including ecology, geography, hydrology, and urban studies.

The family of models called cellular automata (CA) is a simple vehicle to capture and simulate the complexity inherent in dynamic systems. In this paper we document the application of the SLEUTH CA urban growth model to two Portuguese metropolitan areas. These cities have very different geographic characteristics, and were selected to test the model's flexibility to adapt or 'evolve' into different urban environments. Lisbon is the capital of Portugal, and the administratively defined metropolitan area includes large patches of farmland surrounding the mouth of the Tagus River. The urban pattern of Lisbon and its environs is characterized by intense urban pressures, first along main roads and rail lines and, in a recent period, through the development of large suburban developments in rural areas. By contrast, the metropolitan area of Porto is characterized by a coastal Atlantic landscape at the mouth of the River Douro and is surrounded by mountains. The urban pattern grew constantly mainly around its two nuclei (Porto and Vila Nova de Gaia), and the settlements are scattered among many small rural towns and villages with small patches of intensive agriculture and pine forests.

This paper summarizes research conducted to describe, model and predict urbanization in these two metropolitan areas of Portugal (Figure 1). We begin by describing the history of CA modelling and its main elements, pointing out some of the differences between simple and more extended CA often used in urban modelling. Then, the SLEUTH model is described, explaining the original CA theory, and its novelties. The third part

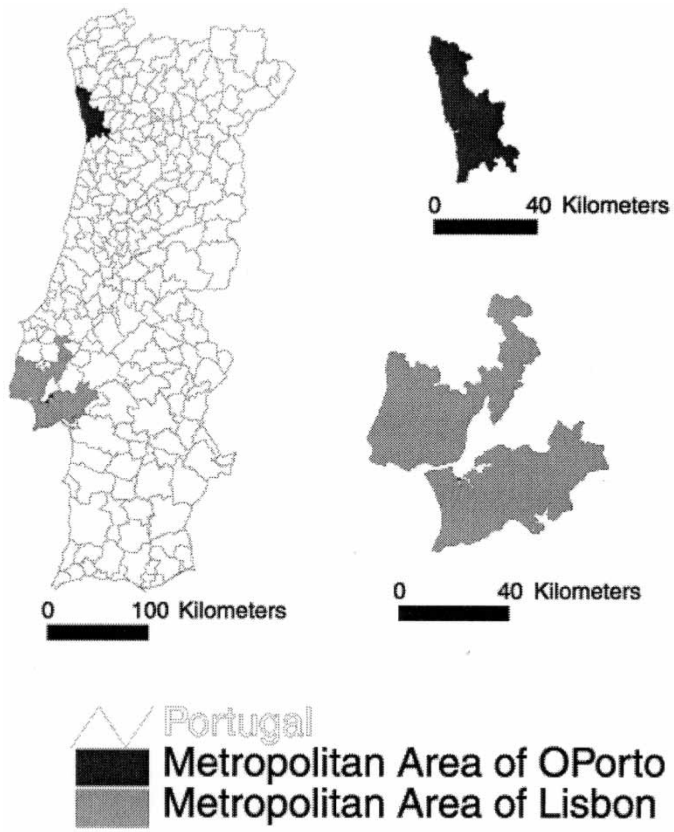


**Figure 1.** Location of the Metropolitan Area of Lisbon and the Metropolitan Area of Porto, Portugal

describes the database used as model input for the Lisbon and Porto Metropolitan Areas. The fourth and fifth parts describe the process of running the model, its calibration with historical data, and the future simulations. The correspondence of the SLEUTH model to the original CA theory and the appropriateness of introducing self-modification rules are explored throughout. The sixth part analyses the data resulting from the prediction mode of SLEUTH, and the seventh part returns to the lessons learned from the modeling effort, and their consequences for future work.

## Cellular Automata

Sixty years ago, von Neumann and Morgenstern's "theory of games and economic behavior" (1944) initiated a very important pan-disciplinary paradigm change. Initially conceptualized as an attack of the Hicks-Samuelson variant of neoclassical economics then dominant, "it precludes the emergence in the twentieth century of structuralist analysis" (Leonard, 1995: 731). Influential research was Hilbert's construction in 1899 of the axioms of Euclidean geometry, Zermelo's 1912 link of kinetic theory, quantum mechanics, and parlour games, and Remark's 1929 works on microeconomics. The theory of games "becomes part of a general shift in science which involved, broadly speaking, the abandonment of determinism, continuity, calculus, and the metaphor of the 'machine' to allow for indeterminism, probability, and discontinuous changes of state" (Leonard, 1995: 756). The emphasis was therefore shifted from determinant to structure.

Beyond his academic work, Von Neumann was engaged in an intense collaboration with the military. His work with Standislav Ulam, a renowned mathematician, suggested to him as early as 1950 that simple CA could be given sets of local rules that generated mathematical patterns in two-dimensional and three dimensional space. The key was that global order could be produced from local action (Batty, 1997b: 159).

Von Neumann "called his proposed systematic theory the 'theory of automata'. This theory of automata was to be a coherent body of concepts and principles concerning the structure and organization of both natural and artificial systems, the role of language and information in such systems, and the programming and control of such systems" (Von Neumann, 1966: 18). In 1970, Conways's 'game of life', popularized by Gardner in his column in *Scientific American*, exposed these ideas through other fields of science. Simple simulations of death and life in a CA game proved the striking similarities between real life and simulated life in a computer.

Strict CA came into geography through Waldo Tobler who had contact with Arthur Burks at Michigan (a disciple of Ulam's) and was exposed to von Neumann's works, leading to '*Cellular Geography*' (Tobler, 1979). At the University of California, Santa Barbara, Helen Couclelis, influenced by Tobler, and also by Prigogine's work on molecular interactions and their resulting large-scale spatial structures, published '*Cellular Worlds*' (Couclelis, 1985).

Cellular automata are formally expressed rather simply, and their power comes from the ease with which simple preconditions, distributions, rules, and actions can lead to extraordinary complexity. There are several components in a CA: spaces, states, neighbourhoods, and transition rules. The space of CA maps well onto the raster data structure of geographic information systems. Grid space is organized by cells, and for CA models these are generally two-dimensional, rectilinear, and homogeneous. The cells are the smallest units, and must manifest adjacency or proximity. The state of a cell can change according to one or more transition rules, defined in terms of neighbourhood functions. In a standard CA model, the state is usually used as the main attribute to describe the development of a cell. The cell neighbourhood is central to the CA paradigm, the state of any cell depends on the state and configuration of other cells in the neighbourhood of that cell. Two neighbourhoods commonly defined are the von Neumann neighbourhood (defined by 5 cells, the cell itself plus the N, S, E, W contiguous cells), and the Moore neighbourhood (defined by 9 cells, the immediate 8 cells close to the central cell).

Transition rules are decision rules or transition functions of the cellular model, and must be clearly stated. The rules can be deterministic or stochastic, and in theory there can be as many transition rules as cells, but in practice there are only a few. One key element is that the rules must be spatially uniform. They must apply to every cell, state, and neighbourhood, and every change in each state must be local.

Dynamics with a CA require an initial set of states over the cells, and a sequence of discrete time steps. In CA, time is discrete through a simultaneous updating of all cell states after the rules have been applied to the current configuration. When activated, the cellular automaton proceeds through a series of iterations. For each iteration, the cells in the grid are examined in order. Based on the composition of cells in the neighbourhood of that central cell, the transition rules are applied to determine the central cell in the next iteration.

Figure 2 presents an example of a CA. The universe is the matrix, states are dead or living cells, the transition roles are set, and time corresponds to T1, T2, T3. An example applied to urban planning is as follows: the universe is the land, live cells are urban areas, and an example of a transition rule is "urban nuclei below a specific number of households can't pay for facility costs and will be abandoned through time if they become individual households". Therefore, accordingly to figure 2 and the rules, the urban area of the Time 1, will have two households moving to its periphery in Time 2, one of the households will disappear because of the rule. At Time 3, another household moves further into the countryside, once it loses the connection with another urban cell, it becomes isolated and also disappears. Through this simple example, it is possible to understand the consequences of the rule as manifested in the formation of different urban shapes over time. Dynamic simulations, besides their visual impact that promote analysis and understanding of the shape and size of urban growth, also allow for quantitative analysis on the elements that promote, for instance, specific paths of urban growth.

Wolfram (1994: 3–7) outlined a number of characteristics that CAs possess:

1. The correspondence between physical and computational processes is clear;
2. CA models are much simpler than many mathematical equations, but produce results that are more complex;

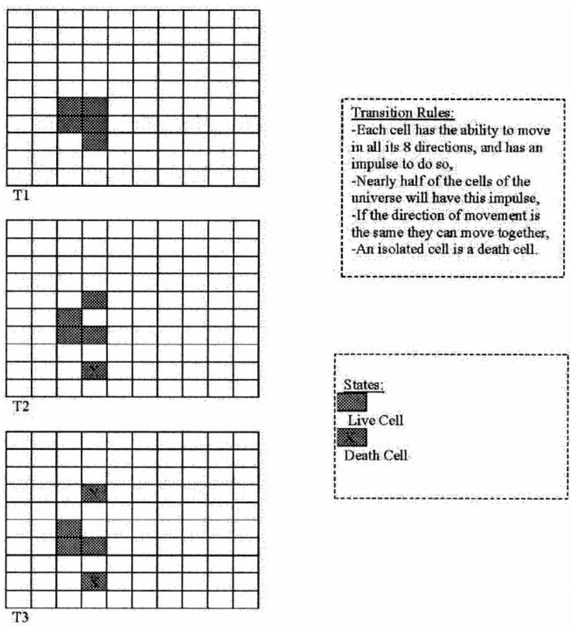


**Figure 2.** An example of a CA running at different time steps (integrating: time, transition rules and states)

3. CA models can be modelled using computers with no loss of precision;
4. CA can mimic the actions of any possible physical system;
5. CA models are irreducible.

These properties of CA imply that there is no pre-knowledge of a global structure and that any global pattern created by CA is not prescribed or predetermined but rather emerges from purely local interactions. Cellular automata models are based on the premise that it is possible to describe the complex patterns of natural phenomena by modelling the simple rules that govern the actions of the component parts, and consequently, emergent patterns and properties can be identified. A classic example of an emergent phenomenon in the game of life are 'gliders', spatial configurations that endure by continuous movement, and oscillators, that seem to be stable *in situ* by oscillating between two complimentary spatial patterns.

Cellular automata can be seen as discrete models of spatio-temporal dynamics where local and regional behavior are interrelated. The work of Prigogine pioneered the relationships between molecular interactions in chemical reactions, and demonstrated the importance of this micro-macro interaction in pattern identification. In the same way the works of Holland (1999), Crutchfield (1995), and Kauffman (1984), have been important in pointing out the emergent properties of random complex automata.

While the patterns obtained with different rules are different in detail, their CAs appear to fall into four qualitative classes, at least for one-dimensional automata:

1. behaviour leads to a homogenous state;
2. behaviour leads to a set of separated simple stable or periodic structures;
3. behaviour leads to a chaotic pattern;
4. behaviour leads to complex localized structures, sometimes long-lived (WOLFRAM, 1984: 5).

The observation that micro-simulations lead to macro-patterns is at the basis of CA. This implies that patterns are imprinted at several scales, giving a fractal character to their CA simulations. Several authors have observed this after applying their CAs. Clarke and Gaydos (1998: 700) stated that "Simple cellular automata are characterized by phase-transitions between behavior types, so that a single model can result in stability, stochastic instability, or chaos". White (1997b: 234) mentions that bifurcations appear in any sufficiently nonlinear system, where new and qualitatively different solutions appear suddenly (as one or more parameters pass a critical value). Batty (1997a: 268) also remarked on this quality: "their patterns repeat themselves across many scales due to the fact that their growth reflects the successive application of the neighborhood principle".

With time came a better understanding of CA in the geographical sciences, and with the integration of real data came the technical possibility of relaxing the assumptions of standard CA that do not fit our experience of cities and regions: non-homogeneity of space; non-regularity of neighbourhoods, different transition functions, probabilistic transition rules, permeability to action at a distance, allowance for time decay, and variable time steps. Some recent applications of CA include several of these variants. These include the incorporation of bigger neighbourhoods, such as the case of 112 cells (White, 1997), the use of hexagonal cells (Sanders, 1997), the use of constrained and stochastic CA with friction at a distance (Ward, 2000; Clarke, 1997; White, 1997), and the idea that binary states have been replaced by several transient states (e.g. gray or 'ghost state' urban growth simulated by Li, 2000: 137).

The range of approaches to CA has also broadened: from urban and metropolitan growth models (Ward, 2000; Li, 2000; Batty, 1999; Clarke, 1998, 1997), to CA migration of workers (Sembolini, 1997), to simulation of urban forms (Wu, 1999, 2000; Batty, 1997a), to modelling systems of cities and regions (White, 2000; Sembolini, 1997; Sanders, 1997; Portugali, 1995), to CA's use in international migration (Portugali, 1995), to micro-economic theory and environmental economic efficiency locations (Wu, 2000; Webster & Wu, 1999), and to models of competitive behaviour (Benati, 1997). With this broadening of CA, new geographical areas have been studied: from China and Portugal, to the USA, Canada, UK and Mexico.

With this deeper knowledge of CA, new questions and problems arose at the level of implementation, concerning model results and the conceptual application of CA. One of the problems, pointed out since the origins of CA in the social sciences, lies in one of the basic principles of CA: the lack of action at a distance (Li, 2000: 133; Batty, 1997b: 161). Another problem is the homogeneous time period update, since in reality updates are not independent, and individual decisions influence others, especially within a neighbourhood, in the same time period (Huberman, 1993: 7716).

The introduction of global constraints to the initial sets of CA conditions has been the subject of intense discussion in the literature. Usually, exogenous estimates of amounts of change are used, such as population projections, and the CA 'allocates' the change spatially. Introducing constraints requires two problems to be solved; that numerical values for the constraints be acquired or generated; and that the constraints be incorporated into the transition rules in such a way as to ensure that they are satisfied without violating the logic of the local process modelled by CA (White, 2000: 390; Ward, 2000: 542). It remains to be proven that CA models used in this way behave any different than probabilistic GIS-based constraint allocation methods, such as multi-criterion weighting. Other theoretical questions have been raised, such as the fact that simply by using the overall rate of increase and overall movement rates without concern for the life stages at which movement takes place may introduce very large errors (Hastings, 1996: 1679; Huberman, 1993: 7716).

Problems of back and forward propagation seem also to be a concern. Toffoli (1987: 146) posed questions of reversibility and the problems of applying the inverse rules in non-linear systems. Prigogine questions whether irreversibility throughout what is commonly defined as the direction of time and the theory of dynamical systems, allows the formulation of laws of nature (Prigogine, 1999: 538). Gowithz (1991: i–xiv) stated the forward problem, and the inverse problem: "the forward problem is: given a CA rule, determine (predict) its properties. The inverse problem is: given a description of some properties, find a rule, determinant, or set of rules, which have these properties". A relevant example of this second problem was explored in von Neumann's seminal construction of a cellular automaton capable of reproducing itself.

In summary, while complex systems theory and cellular automata are mature and rich areas of theory, many fundamental questions remain about the suitability of CA for social systems. In particular, they require that cities be reduced to cells and states that may be simple to map, yet generate rules and forecasts that leave much unexplained about how human settlements work. These questions are often lost in the details of model application. We therefore will apply such a model, and then return to discuss the issues in the light of the lessons learned in application.

**The SLEUTH Cellular Automaton Model**

SLEUTH is a CA model developed to forecast urban growth and land use change. SLEUTH is an acronym for Slope, Land Use, Excluded Areas, Urbanization, Transportation, and Hillshade, the input layers that make the model run. Developed by Clarke (1997, 1998) this CA contains the main elements that characterize the core characteristics of CA: it works in a grid space of homogeneous cells, with a neighbourhood of eight cells, two cell states (urban/non-urban), and five transition rules that act in sequential time steps. SLEUTH also incorporates several novelties that bring its behaviour closer to observed urban evolution. Self-modification is permitted, which allows the rules to change in reaction to aggregate behaviour, in particular the overall growth rate. The automated calibration process allows the model to 'learn' the history of the place and simulate accordingly to the most important characteristics, allowing for periods of intense rapid growth, or little or no growth. SLEUTH also allows weighting of cells, besides 0/1, different weights are possible in some of the data layers.

SLEUTH requires five inputs maps: urbanization, transportation, areas excluded from urbanization, slopes, and a hill shaded map (prepared using GIS and then converted to 8 bit GIF images). For all these layers, 0 is a null value, while all the values in-between 1 and 255 are a measured value. The model also requires that the input layers have the same number of rows and columns and are correctly georeferenced, as the model is sensitive to layer misregistration. Urbanization is the most important layer in the model, and for statistical calibration of the model at least four urban time periods or spatial extent 'snapshots' must be used.

Urbanization in the model results from several active elements (stored as files): a seed urban file with the oldest urban year, and at least two road maps that interact with a topographic slope layer, to allow the generation of new nuclei or the outward growth of existent ones. Besides the slope, a constraint or exclusion map represents water bodies, or natural and agricultural reserves that prevent development from happening, with either probabilities or hard criteria. The weighting of the raster layer of roads allows a hierarchy with different values that influence urbanization in different ways, directions and intensities. A final layer, normally hill shading, is required as a cartographic background for the dynamic urbanization display.

The model works in the following way: after reading the input layers, initializing random numbers and controlling parameters, a predefined number of interactions takes place that corresponds to the same number of years. An outer loop executes each growth history and retains statistical data, while an inner loop executes the growth rules for a single year. After each model run, sets of descriptive statistics are computed and saved to a file for the purpose of calibration. There are thirteen scores, and include: $r^2$ population (least squares regression score for the number of urban pixels compared to actual urbanization for the control years), edge $r^2$ (least squares regression score for the length of the urban-rural edge compared to actual urbanization for the control years), $r^2$ clusters (least squares regression score for modelled average urban cluster size compared to known mean urban cluster size for the control years), and the Lee-Sallee index (1975) (a shape index, a measurement of spatial fit between the model's growth and the known urban extent for the control years).

The change rules that determine the state of each individual cell are applied to the neighbourhood of each cell are tuned with five parameters: Diffusion, Breed, Spread, Slope

Resistance and Road Gravity. The total modelled growth is the sum of the four different types of urban growth defined in the CA transition rules. The diffusion factor determines the overall dispersiveness of the distribution of single grid cells and of the movement of new settlements outward through the road system. The breed factor determines how likely a newly generated detached settlement is to begin its own growth cycle. The spread coefficient controls how much outward 'organic growth' expansion and infill takes place within the system. The slope resistance factor influences the likelihood of settlement on steeper slopes, and Road Gravity is a factor that simulates the effect of attracting new settlements onto the road system if new areas fall within a given distance of a road (Clarke *et al.*, 1997: 252; Candau *et al.*, 2000). These coefficients allow the generation of four different kinds of urban growth, Spontaneous New Growth, Diffusive Growth, Spread of a New Growth Center, Organic Growth and Road Influenced Growth.

A practical example of the mechanics of the model follows. In a grid where flat surfaces exist and roads are close by, urban cells will accumulate over several interactions in areas close to and along that roadway, and then spread from this location to new neighbours to yield new growth from this location outwards. The same can happen in locations where at least three urban cells exist in the neighbourhood, allowing, in this case, organic growth to expand from those existing three cells. In areas with no or isolated urban cells without direct road influence, two kinds of urbanization can happen, spread from a newly formed urban centre, or spontaneous new growth can occur if it is possible there. These examples of the model functioning are intended to illustrate the internal mechanics, nevertheless, this is a more complex process with multiple possibilities for non-linear feedbacks among the factors creating the growth.

The use of initial conditions, as previously described, reflect the spirit of the initial CA theory. The authors (Clarke *et al.*, 1997, 1998) included a set of additions to the model by developing a set of self-modification rules in order to control the parameters, allowing the model to modify itself making them closer to what is observed in the real world. This was necessary because only occasionally did the CA behave so as to create the lazy-S urban saturation curve over time, which non-linear behaviour feedbacks made far more common, increasing the likelihood that the model behaviour would match the observed behaviour. With each run, the model records an average history of urban growth, using Monte Carlo simulation. A single simulation's 'success' is in maximizing the 13 measures that compare the modelled growth to the observed, and the model is tested exhaustively until a best solution emerges.

During any one simulation, the detection of intense growth periods (boom) or periods of little or no growth (bust), changes the behaviour control parameters. When the rate of growth in any year exceeds a critical value, the Diffusion, Spread and Breed factors are increased by a multiplier greater than one. This encourages diffusive, organic and road influenced growth, reproducing the tendency of an expanding system to grow even faster. In contrast, when the system growth rates fall below another critical value, the diffusion spread and breed factors are decreased by a multiplier less than one, similarly to what would happen in depressed or built-out areas. Two other self-modification rules can play an important role in the case of normal growth (representing linear growth). As the road network densifies and enlarges, the road gravity factor is increased. As the percentage of land available for development decreases, the slope resistance factor is decreased, allowing expansion onto steeper slopes, up to a maximum feasible buildable slope value. With time, the spread factor is also increased, which accelerates urban expansion on flat land.

Calibration plays an important role, not only by allowing an improved fit between the simulation and the actual data by refining the control values, but also, because it allows us to see, in a very clear way, how these self-modification rules contribute to the CA behaviour (Silva Clarke, 2002; Clarke *et al.*, 1998). The method of calibration has been termed 'brute force': all combinations and permutations of the five control parameters are searched in a method designed to lead to at least a local best solution, though not a provable optimal solution (Clarke, 2003). The calibration process is compute-intensive, and has led to experiments and methods to speed up the routines, including parallel processing and supercomputing.

## Input Data from the Lisbon and Porto Metropolitan Areas

Cellular Automaton (CA) have proliferated outside of GIS in spatial analysis and planning mainly due to the inability of GIS to perform modelling, especially in a computationally intensive setting. GIS has limited ability to perform repetitive operations (especially on large volume data sets), and has only a weak ability to handle dynamic spatial models (Park Wagner 1997: 213). While several of the commercial GIS vendors are trying to address this absence nevertheless, the capabilities of GIS in data manipulation make it critical in preparing the data sets (new map extents, projections, grid resolutions, co-registration, editing and visualization of the data), and GIS has the potential to be a very important engine for cellular automata (Goodchild Longley, 1999; Anselin, 1999). The advantages of linking CA and GIS have been discussed extensively with respect to CA (Li, 2000; Wu, 1999; Clarke, 1998, 1997; Wagner, 1997; White, 1997). The linkage between CA and GIS varies, and has been characterized as of three types: stand-alone, loosely coupled and fully integrated (Goodchild, 1992: 417; Park Wagner, 1997: 215).

SLEUTH is a stand-alone model, *but* requires a data set to be built in GIS in order to run. The GIS and CA integration in SLEUTH has been described in three phases: an initial phase of tight coupling when the data set is worked to feed the model; a second phase of loose coupling during exploration of the results of the application; and a third phase, also of loose coupling where the predictions generated are introduced again in GIS to allow further display and analysis (Clarke & Gaydos, 1998: 701).

For the Lisbon and Porto Metropolitan Areas, compilation of the data was a straightforward process in the case of the Lisbon, but a harder task for Porto. The database for Lisbon was built for a longer time period and was documented. The Porto database was completed only in December 1999. Classification of Landsat imagery was also easier in the case of Lisbon. Tables 1 and 2 present a synthesis of the different layers required and their grid values.

The urban extent data was a result of a supervised classification of Landsat imagery. The urban-built up land, including buildings, asphalt, concrete, suburban gardens, and roadways, was classified, extracted and represented as binary files (urban/non urban). The Landsat data resolution of 30 metre pixels limited the minimum unit possible to extract to four adjacent pixels (3600 square metres), therefore, elements below that threshold were automatically clumped by predominance. The classified data was then georeferenced, using the transportation layer (the root mean squared positional error for all of the images was below half the cell size), resampled to a $100 \times 100$ m grid, and clipped to the metropolitan area administrative boundary (a similar process of resampling and clipping the layers occurred in all the other layers).

**Table 1.** Description of the input layers for the Lisbon Metropolitan Area (AML) data-base

| | Description | | | | |
|---|---|---|---|---|---|
| AMP layer | no layers | no years | no classes | Cell value | Source of data |
| Slope | 1 | – | – | 0–76° (0–373%) | CNIG-RCV* |
| Excluded | 1 | – | 1. Ecological reserve (REN)<br>2. Agricultural reserve (RAN) | 1. REN = 100<br>2. RAN = 50 | Municipal master plans |
| Urban | 4 | 1975, 1984, 1995, 1997 | 1. Urban | | Landsat images (MSS, TM: Eurimage, USGS) |
| Transportation | 2 | 1987, 2000 | 1. Base Roads (BR)<br>2. Highways (HW)<br>3. Proposed Roads (PR) | 1. 50<br>2. 100<br>3. 25 | 1987 roads provided by ACP<br>2000 roads provided by PROT |
| Hillshade | 1 | – | | 0–365°<br>Azimuth-315<br>Altitude 45 | DTM with $100 \times 100$ m cell size |

*Centro de Informação Geográfica (CNIG, Portugal), Project "Rede de Corredores Verdes"

The transportation layer was derived from several sources. In the case of the Lisbon Metropolitan Area, the most recent year was extracted from the Regional Plan for the Lisbon Metro Area (the acronym is PROT-AML). The oldest year was obtained through the following process: using a 1987 Road Map from ACP (Automóvel Club de Portugal), the roads that did not exist in 1987 were subtracted from the PROT-AML, until it matched the ACP 1987 map. In the case of the Porto Metropolitan Area, the 2000 map was a result of the compilation of the Municipal Master Plan roadway maps, and several other forms of auxiliary data information, and the same process was applied to obtain the 1987 road map. The model allows weighting of the different roads with values that reflect their importance to the transportation system, so the roads were ordered by degree of importance in both metropolitan areas, and three classes were defined: surface roads, highways, and proposed roads. We decided to equally distribute the values between 0 and 100, being aware that further studies need to be done in order to be sure of the degree of importance in the network. The assigned values were the following: highway 100, base roads 50, and proposed roads 25.

The excluded-areas layer contains the water bodies and land where urbanization cannot occur. In both case studies, the information was taken from the Municipal Master Plans, predominately from two classes defined by law: the 'Ecological Reserve' and the 'Agricultural Reserve'. For both the Lisbon and Porto Metropolitan areas, this layer also contains weight values indicating probabilities of exclusion. In the Lisbon database, we decided to attribute a value of 100 to the Ecological Reserve and 50 to the Agricultural Reserve. One hundred means that no development is allowed and 50 that some

**Table 2.** Description of the input layers for the Porto Metropolitan Area (AMP) data-base

| | Description | | | | |
|---|---|---|---|---|---|
| AMP layer | no layers | no years | no classes | Cell value | Source of data |
| Slope | 1 | – | | 0–76° (0–373%) | CNIG |
| Excluded | 1 | – | 1. Ecological reserve (REN)<br>2. Agricultural reserve (RAN) | 1. REN = 100<br>2. RAN = 50 | Municipal master plans |
| Urban | 4 | 1975, 1987, 1997, 2000 | | | 1975, 1987, 1997, Landsat images (MASS, TM: Eurimage and USGS); 2000 Municipal master plans |
| Transportation | 2 | 1987, 1999 | 1. Base Roads (BR)<br>2. Highways (HW)<br>3. Proposed Roads (PR) | 1. 50<br>2. 100<br>3. 25 | 1987 extracted from AICP<br>1999 Municipal master plans |
| Hillshade | 1 | – | | 0–365°<br>Azimuth-315<br>Altitude 45 | DTM with $100 \times 100$ m cell size |

*Centro de Informação Geográfica (CNIG, Portugal), Project "Rede de Corredores Verdes"

development is possible. Once again, tagging these values with the specific land use reflects our knowledge of Portuguese land conservation, but further studies need to be done in order to assign values with more certainty.

We compared the Landsat urbanized areas with the initial maps of Agricultural Reserve (RAN) and Ecological Reserve (REN), and demonstrated that the prohibition of urban growth by law in both cases was not effective. We decided to keep REN as non-developable and RAN as partially developable. REN included major parks, habitat areas and riparian corridors, and therefore tends to have more law enforcement. The Agricultural Reserve (RAN), seems to be less protected when compared with REN, and therefore was given the possibility of having some development.

Comparing the simulated past urban years with the Landsat classification (Figure 3), there is not an absolute match between them, the simulated image presents the urban cells as more scattered. This is due to the fact that we decided to prevent urbanization from happening in the RAN and the REN areas, as defined by Portuguese law, therefore the model keeps past urbanization more concentrated.

The slope layer is the average percent slope computed from a 100 metre digital terrain model, and lastly the hillshade layer was used as a visual display of model results in the graphic version of the model.

Three final steps were necessary before the data could feed the model. The first action was to make sure that all the files had the exact final number of rows and columns,

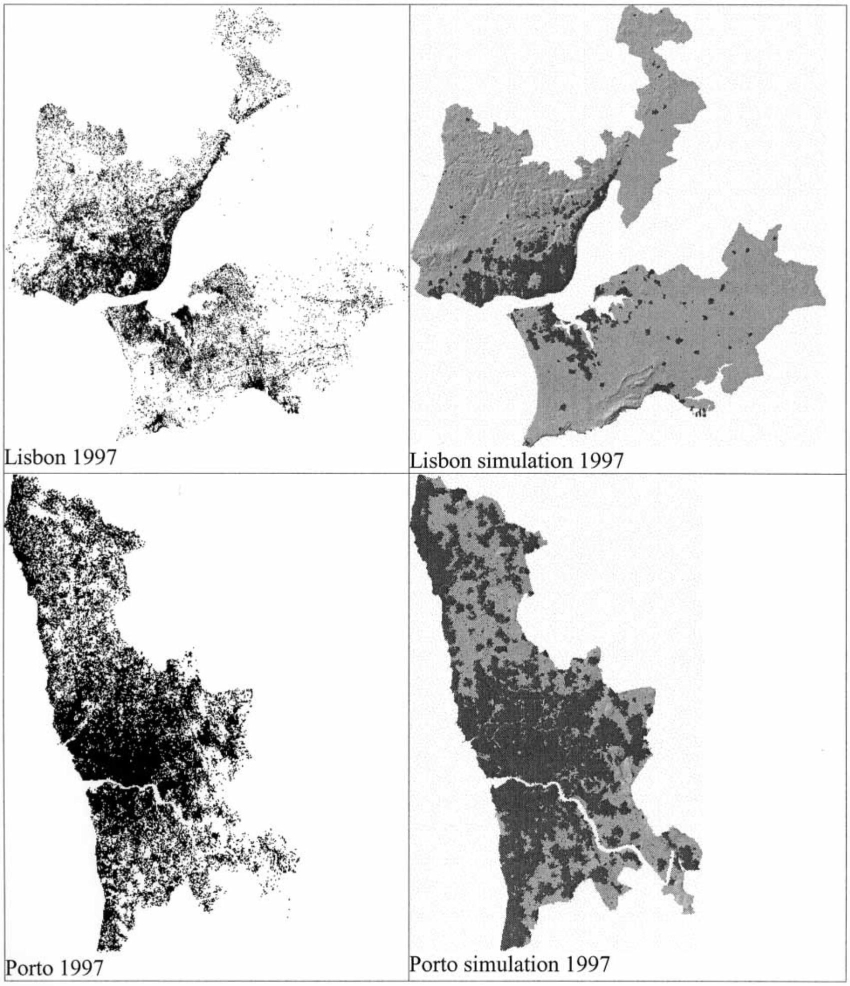


**Figure 3.** Observed urbanization and simulated urbanization in 1997, for Porto and Lisbon Metropolitan Areas. This simulation assumed that, as stated by Portuguese law, no growth could happen in the Ecological Reserve (REN=100), and little growth could happen in the Agricultural Reserve (RAN = 50). The white cells in the two images represents actual urban pixels, the dark gray cells in the simulated images represent simulated urban cells

784 × 836 pixels for Lisbon, and 347 × 563 pixels for Porto. The second action was the conversion of all the GIS files to a GIF file format, and thirdly to be sure that the files had the naming conventions the model would read, as these are standardized and used for the data input part of the modelling.

## Running the Model

The model is first run in a calibration phase to obtain a suitable set of parameters. More precisely, the model was run in three different calibration phases (coarse, fine and final). This process, described elsewhere (Silva & Clarke, 2002), explores the parameter space in a sequential multi-stage reduction by extensive automated exploration of the parameters that control the system's behaviour. The calibration phases allow the model to simulate urban growth from the past into the present with a very high degree of fit between the simulated years and the control years (r-squared of 0.91 in the case of Lisbon, and 0.99 in the case of Porto – Table 3). These high values imply that it is possible to simulate almost exactly the number of urban pixels from the control years, yet it is nevertheless very difficult to simulate exactly the way these urban pixels are organized in space (the urban shape), the shape index reflects this statement with values of correspondence of 0.58 for Porto and 0.35 for Lisbon. This was at least partially due to the fact that we decided to constrain the model to follow Portuguese Law by forbidding development in the reserves (RAN and REN).

As seen in Figures 4 and 5, the behaviour of the Lisbon and Porto Metropolitan Areas simulations is visually different but familiar to those familiar with both places, and easily confirmed by the local history and scores resulting from the model calibration. The calibration process for the two cities has been documented in depth (Silva & Clarke, 2002).

Both the Lisbon and Porto Metropolitan Areas underwent intense growth from the beginning of the 1970s until the present, reflecting the post-revolution return from the colonies. According to Rodrigues (1999: 313) between 1994 and 1998, 40% of the development permits in the country were given in these two metropolitan areas. This intense growth assumed different shapes, directions and intensities in each area. From the

**Table 3.** Best overall final calibration results for Lisbon and Porto Metropolitan Areas

| | AML | | AMP | |
|---|---|---|---|---|
| Score/ | $784 \times 836$ | | $347 \times 563$ | |
| Composite score | 0.15 | | 0.48 | |
| Compare | 0.90 | | 0.97 | |
| $r^2$ population* | 0.91 | | 0.99 | |
| Edges $r^2$ | 0.78 | | 0.98 | |
| Cluster $r^2$ | 0.85 | | 0.99 | |
| Leesalle | 0.35 | | 0.58 | |
| | Final Calibration | After Self-modification | Final Calibration | After Self-modification |
| Diffusion | 16 | 19 | 20 | 25 |
| Breed | 57 | 70 | 20 | 25 |
| Spread | 50 | 62 | 40 | 51 |
| Slope | 25 | 38 | 45 | 100 |
| Roads | 30 | 43 | 20 | 75 |

–The overall composite score (all scores multiples together) is bigger in Porto. The compare score (comparison of modelled final population** to real data final population**) and the $r^2$ population (least squares regression score for modelled urbanization compared to actual urbanization for the control years) are both similar

–The Edges $r^2$ (least squares regression score for modelled urban edge count compared to actual urban edge count for the control years) and the Cluster $r^2$ (least squares regression score for modelled urban clustering for the control years) are smaller in Lisbon. Due to the fact of the road oriented and nuclei organic growth, orignates very defined shapes, and ages 'harder' to replicate compared to known urban clustering

–The Leesalle index (a shape index, a measurement of spatial fit between the model's growth and the known urban extent for the control years) also smaller for Lisbon reinforces the previous indexes

–The Diffusion, Breed, Spread, Slope and Road values include the final calibration values and the values after self-modification

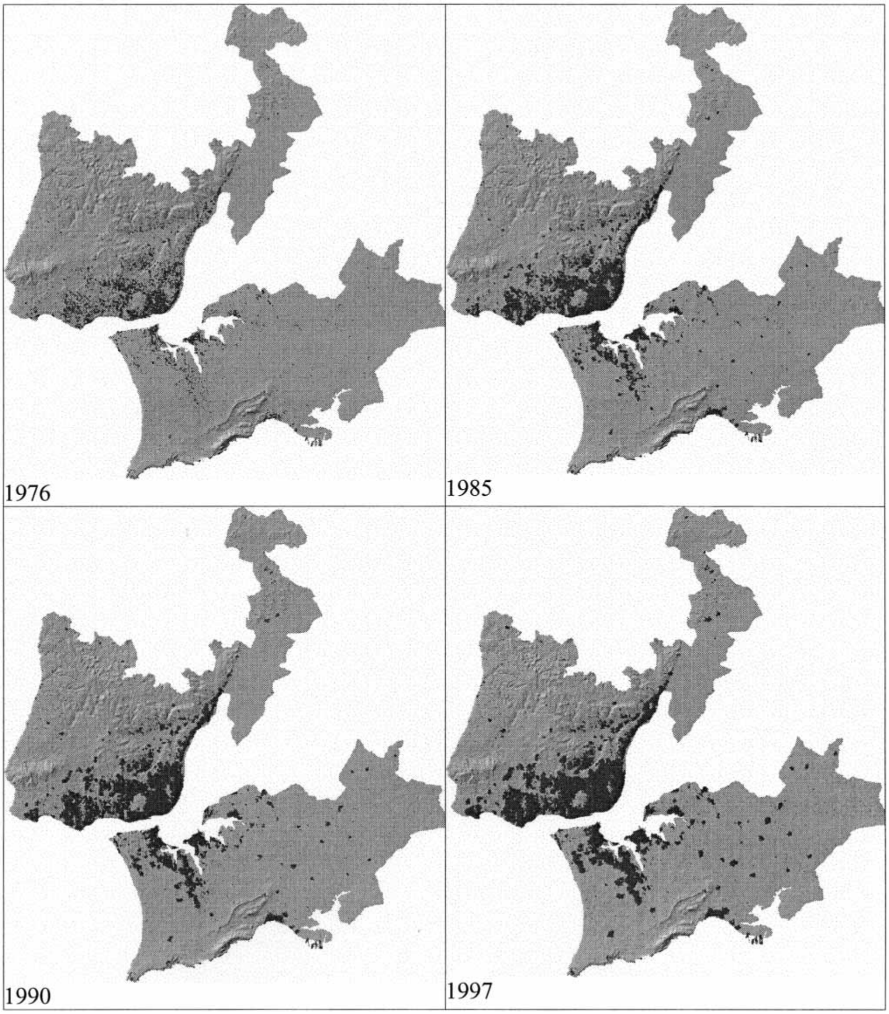


**Figure 4.** From 1976 to 1997 (selection of 4 years for the yearly simulation). The Urban Evolution of the Metropolitan Area of Lisbon (AML). The dark gray cells represent urbanization growth, the gray hillshade background was clipped to the administrative boundary of the AML. White represents the outer area of AML, (mainly the Tagus estuary to the SW, and land at NE)

1970s to the present, the Lisbon Metropolitan Area followed a more ‘ordered’ growth, with an urban axis expanding from the main urban nucleus: Lisbon, Oeiras, Alamada and Seixal. Visual inspection of the Porto Metropolitan Area reveals a scattered urban pattern throughout the entire metropolitan area with high densities around the cities of Porto, V. N. Gaia, Matosinhos and Povoa do Varzim.

These differences are reflected by the model parameter values resulting from the final calibration phase (Table 3). The five coefficients that both control and describe the behaviour of the system fall into the range of 0–100, allowing the user to understand in a comparative way the contribution, of each element to the urban pattern. Calibration of

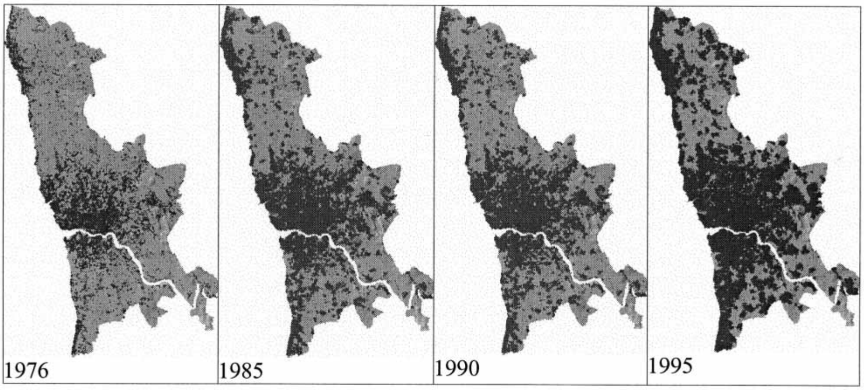


**Figure 5.** From 1972 to 2000 (selection of 4 years for the yearly simulation). Urban Evolution of the Metropolitan Area of Porto (AMP). The dark gray cells represent urbanization growth, the gray hillshade background was clipped to the administrative boundary of the AMP. White represents the area outside the AMP (The Atlantic Ocean to the west, and land to the East)

SLEUTH gave different values of Diffusion (16 in the case of Lisbon and 20 for Porto), suggesting that the overall dispersiveness of Porto is greater. The values of Dispersion and Road Gravity seem to reinforce this conclusion. Road influence has bigger values in Lisbon than in Porto (30 to 20) and organic growth is more intense in Lisbon than in Porto (50 to 40). These conclusions also reinforce the validity of CA (and of this specific CA) to help in understanding complex phenomena through micro-macro analysis, where the understanding of the particular behaviour of the individual elements of the system discloses important patterns and processes at a regional scale (Clarke *et al.*, 1997).

In the two case studies, inductive and deductive knowledge seem to reinforce each other (Silva, 2001). Porto Metropolitan Area's past absence of a regional plan has led to a more 'unorganized' urban system; but the recent decision to impose a major regional transportation plan is beginning to re-organize the urban pattern in the metropolitan area. The model seems to be able to disclose both past characteristics (through calibration) and the more recent behaviour (through self-modification). In the case of the Lisbon Metropolitan Area, the development of a series of regional plans imposed a more 'orderly' urban growth.

Both Metropolitan Areas have been subject to intense urban pressures through time. In the case of Lisbon during the last three decades, efforts to compete with other European capitals have placed an emphasis on the transportation system. National transportation plans laid out the road and rail networks in Lisbon and connected the shoreline between Lisbon and the densely populated industrial district of Porto. Plans for the modernization of infrastructure with major consequences for today's urban form began during the 1960s through the development of the 25 de Abril bridge, and the construction of highways. At the regional scale, two plans were developed; and, although these plans were never implemented in whole, their transportation structure component was. These two regional plans (one developed in 1964, and a second first presented in 1992), defined a set of N-S and E-W radials from Lisbon, as well as two major circulars that led to the current urban form. The Lisbon Metropolitan Area contains 2,554,240 inhabitants in an area of 3128 km$^2$ with a population density of 817 people/km$^2$. Several structural urban characteristics particular to the Lisbon Metropolitan Area are apparent: rapid spread of tertiary centres in the municipalities close to Lisbon; new urbanization along the main high speed roadways due to the increase in car usage; and the development of smaller residential areas all over the metropolitan area (Silva, 1999; Viegas, 1989; Gaspar, 1997).

The Porto Metropolitan Area has a population of 1,196,850 inhabitants, an area of 817 km$^2$, and a population density of 1465 people/km$^2$. The main factors shaping current urban form was not transportation, but population growth and the location of industry. More importantly, the state authorities use of a polycentric vision for the dispersion of growth was a main shaping factor (Cardoso, 1996; Vasquez, 1989). This approach was an attempt to extract advantages from the settlement history and its scattered population and activities. Finally, the absence of regional planning for the area that now comprises the Porto Metropolitan Area further emphasized the already disperse character of population and land use.

Unlike the transportation network in Lisbon that acted as a structuring element for urban growth, Porto's scattered high-density population and industrial polycentric model prevented centralized transportation planning, and the mapped and modelled data seem to reflect this character. The stepwise adaptation of the SLEUTH model through calibration seems to reveal properties of the physical characteristics of the two built environments (Silva, 2001). This seems to confirm other CA studies where the self-organization character of settlement systems and "the 'urban transition' at the scale of the whole system is made through local and competitive transformations" (Sanders, 1995: 289).

Urban form as a product of micro interactions, and the emergence of regional patterns from local, need further explanation. Sanders' reference to the urban transition at the scale of the whole system emphasizes a particular character of this kind of complex system. Nevertheless, it is unreasonable to think that all the patterns will be observed from the most local pixel to the entire globe, there is a set of discontinuities where some micro patterns are lost and others emerge. Factors explaining the choice of a single land parcel by an individual citizen, for example, differ from those influencing a developer seeking to build an entire neighbourhood. Consequently, a constant evolution from local to global by a linear process seems unlikely to exist. As Prigogine (1999: 538) pointed out "the main result of our work is the formulation of microscopic laws of nature which are expressed in terms of probabilities (and not trajectories or wave functions) and lead to time symmetry breaking".

These 'phase transitions' (Clarke & Gaydos, 1998: 707) in SLEUTH are enhanced by the self-modification rules, "In geographical terms, this means that different periods of time should be dominated by different growth behavior, and by increasing spatial adaptation to the local environmental conditions".

It is possible to save the temporally varying set of SLEUTH parameter values resulting from the self-modification rules. The self-modification rules alter coefficient values during a run, so the finishing values of all coefficients are used to find the final best results that describe the boom and bust periods of the system. This is even more important because, through time we must assume that only two trends might prevail:

1. urban growth stabilizes, and in this case the final calibration values and the self-modified values will converge;
2. urban growth increases.

In the case of increased urban growth, the amplitude of urban growth from the final calibration phase to the self-modification values might reflect the intensity of urban pressure in the more recent periods. In both cases it is important to verify if the hierarchy of the coefficients is the same for both final calibration and self-modification. If different, it might imply among other things that we are heading to a different kind of metropolitan shape and size ('a new phase-transition' or a 'time symmetry breaking').

In the model application for both Porto and Lisbon the parameter values changed from {16,57,50,25,30} in the final calibration to {19,70,62,38,43} in self-modification in Lisbon, and changed from {20,20,40,45,50} to {25,25,51,100,75} in Porto (Table 3). We conclude that there were elements that caused a behaviour change, in other words, the high investment in particular kinds of roads, and particularly high volumes of immigration, caused a discontinuity in the speed, direction, and shape of past growth, there-by, signalling a phase-transition in the urban growth (Silva & Clarke, 2002; Silva, 2001).

In Porto the element that seems to contain urbanization from growing ubiquitously is the slope factor. In the case of Lisbon, it seems that the most important element is the value of Breed (which controls the creation of new-detached growing nuclei). These are the most important elements controlling the behaviour of the both Lisbon and Porto Systems. Comparison of the values before and after self-modification for the Lisbon Metropolitan Area does not reveal such a mutation, the values that seem to be predominant remain so.

Comparing behaviour parameters before and after self-modification for Porto it is possible to again verify that slope was the main growth control factor. If the amplitude of values before and after self-modification reflects phase changes, another important element that might also reflect such changes is the Road Gravity. In Porto, outward-organic growth (spread) has higher values than Road Gravity; yet self-modification increased the importance of roads in the behaviour of the system. Road Gravity moved up to the second position of importance in the system after self-modification, from third.

Our analysis shows that the historical supposedly constant growth of the Porto Metropolitan Area is instead 'arrhythmic' growth. Changes in the rate of growth seem to be propelled by a different factor (new fast traffic lanes) and consequently suggest a new phase-transition that probably will reshape the future scattered urban landscape of Porto. Perhaps in the future we will observe a reorganization of activities and populations accordingly to an increasing importance of highways in the system. If so what will the Porto Metropolitan Area lose/win? More intriguing is to ask whether we can promote such a kind of phase-transition in the future in order generate more sustainable urban forms? The model, at least, gives us one platform on which to conduct experiments to this end.

## Forecasts

Validity is a measure of how well the model captures the inherent qualities of a real system in terms of replicability, prediction and structural integrity (Deadman, 1993: 154). For policy makers and elected officials, modelling with CA has the potential to demonstrate the outcome of policies before they are implemented, to evaluate alternative scenarios, and to avoiding serious and irreversible errors. For researchers it is the chance to model and understand a wide variety of natural and cultural phenomena contributing to the process of land transformation (Wu, 1999: 202; Ward, 2000: 540).

If it is possible to verify validity, then the sustainability in future scenarios can be more than a vague guideline. As Li points out (2000: 133) a new paradigm for thinking about urban planning emerges. It is possible to embed some constraints in the transition rules of cellular automata so that urban growth can be rationalized according to a set of pre-defined sustainable criteria, and so explore a sustainable urban future through simulation.

In the case of the two metropolitan areas studied, the first hypothetical question posed was: what if these metropolitan areas keep growing the same way (in a sort of trend scenario – the same regional form, with the same elements constraining its behaviour)? What would be the image of these regions 25 years in the future? Figures 6 and 7 present these scenarios. It is possible to state that the cities' historical characters are imprinted in the

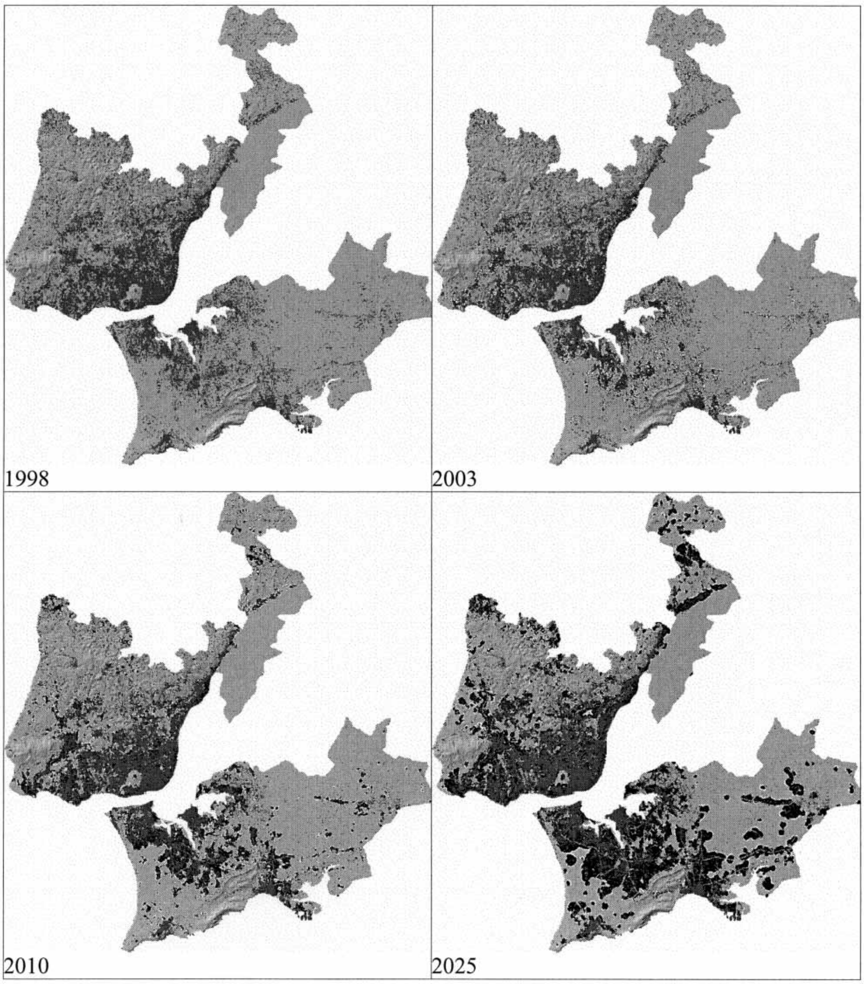


**Figure 6.** One scenario of urbanization for the Metropolitan Area of Lisbon (AML). Besides the gray background and dark gray, already visible in the previous images. Two other colours can be observed in this image, as a result of the Monte Carlo simulation: white cells inside the metropolitan area boundaries represents median/low probability of change, or the formation of new urban nuclei, and black represents high probabilities of change to urban cells selection of 4 years for the yearly simulation

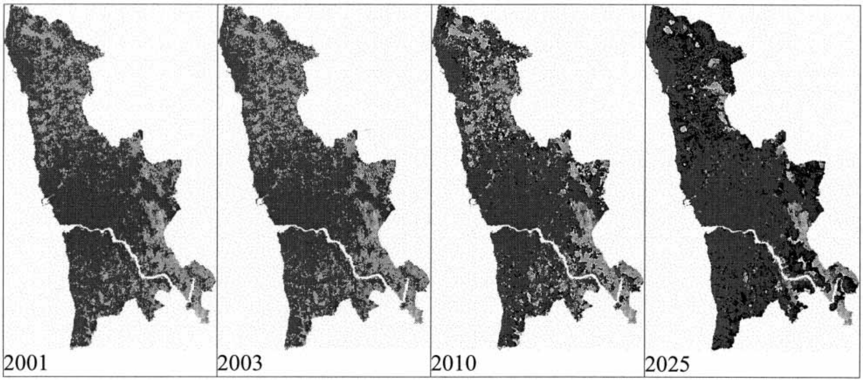


**Figure 7.** One scenario of urbanization for the Metropolitan Area of Porto (AMP). Besides the gray background, the dark gray, already visible in the previous images. Two other colours can be observed in this image, as a result of the Monte Carlo simulation: white cells inside the metropolitan boundaries represents median/low probability of change, or the formation of new urban nuclei, and black represents high probabilities of change to urban cells selection of 4 years for the yearly simulation

simulated future trend. Compared to the historically dispersed Porto, Lisbon's forecast growth continues to appear more organized toward the existent urban nuclei and along main roads, which tend to generate new urban nuclei in high accessibility locations.

Besides these two overall urban patterns, other emergent patterns can be seen at the regional scale. One pattern is the development of what is commonly known as 'edge cities' (cities 'born' as a result of the transportation system, lacking the traditional old central city, and having a 'placeless' nature). An example can be seen in the south-east area of the Lisbon Metropolitan Area. Another emergent property seems to be the densification of urbanization in the northeast municipality (there is a new airport programmed for nearby, the model without knowing, seems to reflect that). In the Porto Area, historical characteristics seem to be the constant densification and growth of population over time structured around an old transportation system (with narrow and highly intertwined roads and transit lines). Nevertheless, the kind of transportation system (wider and faster roads with a regional impact) now under construction will bring with it a different kind of emergent urban pattern. Similarly, will more intense and regular boom and bust phases, in a system historically characterized by constant and continuous growth, similarly mark a phase transition in urban form (Silva & Clarke, 2001)?

The emphasis on the dynamics of development shows the importance of the contribution of CA modelling to urban theory, in the empirical investigation of urban pressures and prediction and decision support. One of its major contributions rests upon the importance of developing and visualizing scenarios that support decision-making, and that make the planning process more transparent (Xiang & Clarke, 2003; Barredo, Kasanko, Mccormick Lavalle, 2003; Adam, 2003).

The forecasts for Porto and Lisbon highlight areas of high urban pressure, growth trends that might be unsustainable, and give visions of metropolitan areas that might be more or less compact, scattered, or with different levels of organization. These forecasts make the public aware of the spatial organization of their metropolitan areas, and decision makers have the ability to adjust the results of planning according to the narrative of one or another metropolitan future (i.e. more of less traffic congestion, natural resources preservation, management of utilities).

Urban theory can gain from these developments. The importance of understanding the critical decision points that lead to a specific urban form, the quantification of the comparative importance of the elements that structuring the metropolitan area, and the identification of phase transitions that might be shifting the metropolitan area's future are some of the relevant elements that require additional study and linkage to theory.

## Conclusions

"There are two general approaches to the study of behavior in CA: 1. Start with specific behaviors in mind and derive a function that will support those behaviors, 2. Start by specifying function and observe the resulting behavior" (Langton, 1986: 124). In this study, we used the SLEUTH CA model (Clarke *et al*., 1997) to apply both ideas, through the use of existing theory on how cities grow, and through the local behaviour of the system. While we have favoured the second approach, with a slight adaptation the model can adjust itself. Changing the parameter sets can allow the emergence of regional patterns throughout micro-simulations, and self-adaptation to time variations. Experiments could test what would happen if Lisbon were to adopt Porto's planning strategy, for example. Alternatively, Lisbon's learned pattern of historical growth could be applied to Porto, to explore what would have happened if it had been the nation's capital. With informed planning as the goal, it might be best to explore enforced behaviour changes and their spatial impacts; such as enforced conservation, growth management and smart growth planning solutions as alternatives to the 'business as usual' forecasts.

The first parts of the paper pointed out the theoretical insights and formal requirements of CA, emphasizing the importance of a simple process of finding out regional complex forms by the understanding of local behaviour without any pre-knowledge of a global structure or any prescribed or predetermined outcome (Wolfram, 1994; Clarke & Gaydos, 1998; Batty, 1999). The application of SLEUTH to these very different metropolitan areas demonstrates this advantage of CA, in that without any prior knowledge of the systems under study (besides the eight input layers) it was possible to characterize the Lisbon and Porto Metropolitan Areas, spatially and temporally, with reasonable accuracy. The 'character' of each metropolitan area was identified, as reflected in the dynamics of the calibrated parameter set and its reaction to self-modification (Silva, 2001), through the use of an analysis of the calibration process itself (Silva & Clarke, 2002). It was also possible to define several emergent regional spatial patterns, such as the development of new edge cities, and to date the phase changes in growth behavior. This is true both in analyzing the past through the model, and in forecasting the future.

The concern expressed that by including modifications to the classical CA model, we might be abusing the philosophy behind CA theory, is certainly fair (White, 2000; Hastings, 1996; Huberman, 1993; Gowithz, 1991). Nevertheless, this is a question that needs to be viewed in the light of model advances and the study of the social phenomena dependent on urban dynamics. SLEUTH mirrors the elements that seem to make CA attractive: that is building an understanding of complex systems through the analysis of how local behaviour generates complex patterns. The comparative model application revealed an emergent urban phenomenon in the 'edge city' form of Lisbon. While the adoption of self-modification into SLEUTH is considered by some as an adaptation that might violate the original CA theory, nevertheless it seems to reinforce the value of CA when applied across different landscapes.

Through self-modification it was possible to further improve the resemblance of the simulation to the reality throughout calibration. The character of scattered populations and activities that Porto had through the centuries (seems to be changing dramatically. In the past, Porto's growth was dominated mainly by spread and slope constraints). A new factor is increasing its importance in the systems behaviour: the influence of roads (as was observed by running self-modification rules). Therefore, self-modification revealed new emergent elements, reinforced others and therefore further emphasizes the original theoretical requirements.

Once applied to a region, SLEUTH 'learns' the region's own characteristics, mirrors the region's own individuality, and reveals new emergent characteristics. We have referred to this as both characterizing a region's DNA, and analyzing how it is mutating and evolving. Therefore testing the validity of the model and its strength create inherent structural validity. Through applying the model, more knowledge was gained that was evident from the data that the model ingested. With further improvements in such models, planners and geographers may finally have basic tools with which to explore the 'genetic engineering' necessary to evolve sustainable cities for the future.

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