Urban Sprawl: A Case Study for Project Gigalopolis Using SLEUTH Model

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Abstract. A brief approach through a CA-based model is perfect for modelling of different urban phenomena at different observation scales. SLEUTH model, situated in Project Gigalopolis, is a powerful tool for description of urban agglomeration and spatial dynamics. In this paper, new applications of this model, other methodological analyses, and sensitivity studies allow us to improve our comprehension of model parameters, taking advantage of this type of synthetic description of reality. Many deductions are possible thanks to the comparison of our studies with other precious databases, already existent, about results of this model.

1 Introduction

We can consider Cellular Automata (CA) like analysis tools for complex systems, because the city and its land-use can be seen like a mechanism, or parts interacting between themselves, in a sort of autonomous systems [1]. Cell changes in a CA are spatially and temporally self-correlated, and they simulate some properties of urban decision process, subdivided in different zones (i.e. zoning policies). A particular really interesting phenomenon that we want to study is the so called urban sprawl, which is an uncontrolled and really ungovernable growth of urbanized areas with a low density level, that acts outside the cities or among different close cities, with several territorial and environmental consequences. To avoid the effort in building different models for the same subject, not really different one from the others, the idea of the *Project Gigalopolis* was born from a collaboration between the University of California of Santa Barbara and United States Geological Survey, which proposed to apply, on a large range of different territories, a CA-based model, already developed: SLEUTH [2][3].

We purpose the first completely autonomous application in Europe, with a critical approach about the use of this model: in particular we want to go deep in the meaning of the parameters, used to describe urban dynamics if different phases of growth, and we want also to individualize the effects through specific simulations and other sensitivity analyses for parameters. The goal of this paper is a contribution for the ambitious Project Gigalopolis, investigating the meaning of the parameters of the model, and the common aspect among different type of urbanized area, so it's possible to build a "DNA of city" through the analysis of the outgoings produced by SLEUTH. Experiences and results come out from previous applications are the main resource for a deep comprehension of the urban and spatial problems.

S. El Yacoubi, B. Chopard, and S. Bandini (Eds.): ACRI 2006, LNCS 4173, pp. 436 – 445, 2006.

2 SLEUTH Model and Project Gigalopolis

In order to characterize urban dynamics SLEUTH works with a strict structure based on different layers: as we can see from its name, which is the acronym of input data that this model needs, the growth of the city is driven, conditioned, or limited by five factors: Slope, Land use, Excluded areas (where the development of urban areas is forbidden), Urban areas, Transportation network; this factors are represented through different layer, and Hillshade, used as background in visualization.

This model is located inside the recent panorama of the urban modelling as a flexible, robust, reliable tool which can be compared and can be competitive with the other CA models. SLEUTH is an evolution of Urban Growth Model, an AC-based built for the first time in 1998 by Keith Clarke. So it is structured in two different modules, which can be activated independently: UGM (Urban Growth Model), that simulate the urban growth, and Deltatron, that allow observing the changes in land uses [4]. In its main module, SLEUTH is a probabilistic CA with Boolean logic (for example a cell can be only urbanized or not urbanized), and with only five parameters; this approach justify the use of "*brute force*" calibration based on the research of parameters in determinate ranges which are progressively reduced. This model is valued for the parameters ability in adjusting and representing, in a careful way, different phenomena of various areas and regions; then theoretically there isn't any limit in dimension of the studied area: there are case studies about a whole region and other application about a single city.

2.1 Model Parameters and Growth Rules

The time unit of the urban growth simulation is the growth cycle, and it corresponds to one year. Urban growth dynamics in UGM module (which provides probabilistic information) are modeled using four sequential rules, like four steps of a cycle; all the cells which constitute the whole automata are update on the whole grid after each rule application.

Five parameters (with values between 0 and 100) influence the way how the transition rules, which describe growth and transformation of the city, can be applied.

1. *Dispersion coefficient* (DI): it controls the number of time that a cell is randomly selected to be urbanized during the application of spontaneous growth law.
2. *Breed coefficient* (BR): it determines the probability of an urbanized cell, in the spontaneous growth phase, to become a new urban core which has the possibility to evolve (new spreading centre). Moreover BR is used road-influenced growth phase, determining the spread along a road.
3. *Spread coefficient* (SP): it defines the probability that a cell, which is part of a spreading centre (a cluster with at least two urbanized cells, in a 3x3 neighbourhood), generates another urbanized cell in its neighbourhood.
4. *Slope resistance* (SR): Slope above 21% can't be urbanized. The slope coefficient determines the weight of the probability that a location may be built up.
5. *Road gravity coefficient* (RG): it defines the maximum influence distance for each road on urbanization probability. It depends also from input map dimension.

The urban growth dynamic, implemented in UGM sub-model, is defined by four steps, depending on the previous parameters: *Spontaneous Growth*, *New Spreading Center Growth*, *Edge Growth*, *Road-influenced growth*. After these phases, there is the self-modification process; without it the model produces linear or exponential growth, which is quite far from reality: growth coefficients do not necessarily remain static throughout an application. In response to rapid or depressed growth rates, the coefficients may be increased or decreased to further encourage system wide growth rate trends.

In order to perform Deltatron module is necessary to predispose input data about land use changes. Dynamics we have already seen start from assumption that the urbanization process is the engine of changes in non-urbanized land cover. Land cover modelling is based on changes of virtual entities, called Deltatron (which represent different type of classes we can consider) described in 4 phases: *Initiate change, Cluster Change, Propagate change, Age Deltatron..*

2.2 Project Gigalopolis

Project Gigalopolis deals with the problem of the modelling of urban growth dynamics, which nowadays have overcome the regional scale to take a global dimension, studying the sprawled city phenomenon. Applying SLEUTH model at the greatest number and different types of territories (this software is freeware at http://www.ncgia.ucsb.edu/projects/gig.html) it's possible to analyze the urban sprawl phenomenon at a global scale and derive some conclusions, with general validity, about the trend of urban development and of urbanized areas.

In whole theory at the base of this project there is the vision of the urban development as driving force of the spatial changes. Project Gigalopolis offers the possibility to compare results among a large number of case studies in Cellular Automata field applied to spatial analysis: it is allowed the access to database composed by parts of results coming from previous application of SLEUTH model.

Use of this model on a large and heterogeneous range of case studies is made to compare the results and understand the real possibility to build new realistic scenarios of urban development, creating in a long period an efficient modelling system, as swell as to realize shared and updated database to drive local communities in clever and responsible development for urban growth. Generalization and contextualization of obtained results, also for heterogeneous territories, can allow identifying the "DNA of the cities", as different combination of parameters.

3 Methodological Analysis, Sensitivity Studies and Applications

Validity of simulations made with a CA-based urban model directly depends on its capability, after a suitable calibration of parameters, to well fit the system we want to study. So, to evaluate critically the ability of SLEUTH in simulating urban systems, we did a study on an ideal territory characterized by a population distributed according the very general Zipf's rank-size rule, and a simulation of a hypothetical case of urban sprawl. But, first of all, we show the behaviour of the model in respect to the values of its parameters.

3.1 Sensitivity Analysis of Parameters

In general it is not possible to associate one parameter with one growth process in an explicit and univocal way, because the growth parameters BR, DI and RG are highly correlated between themselves. This makes difficult to understand each growth cycle in urban evolution, and we can observe only the reproduction of the overall urban complexity. In order to better define the parameter role, we performed some simulations with representative sets of different urban centres (highly constrained for development, prevalence of the diffusion effect, sprawl effect, etc.), both in ideal and actual territories.

In case of an ideal territory, characterized by spatial isotropy and by absence of previous urban structures (20 years of simulation), given initial conditions, we obtain the greatest growth assigning an high value (80-100) to SP parameter rather than to BR and DI. This allows the urbanization of cells in the neighbourhood of other cells previously urbanized: we can observe exponential growths of urbanized area. With high values of BR we obtain with a good approximation a linear growth in urbanization processes (high values of DI lead to similar results but with a lower velocity in respect to BR). RG shows only a qualitative effect, influencing only the localization of new urbanized cells, but not their amount. If we isolate the effect of one parameter, minimizing values of the others, we observe an opposite situation compared to what we have explained before: the highest urbanization growth is obtained with high values of DI parameter. Moreover SP is quantitatively important, if and only if either BR and DI values are negligible, or there are previous urban agglomerations with a relevant extent (like many urban cores in a metropolitan area).

For real territories, where we have done the calibration using four years of data input (with the possibility to compare the effect produced by a set of parameters with a reference situation), maximizing BR, SP, and DI, we obtained a confirmation of the previous results.

This analysis shows that maximization of RG parameter leads to an high urbanization of more accessible areas in connection to road network, with equal growth rate (due to the values of the other parameters).

3.2 Ideal Behaviours at Two Extremes: Hierarchic Structure and Urban Sprawl

The rank-size rule (power law distribution) describes the emergent attitude of urban systems, which have the tendency of self-organization: the law relates the population of a city classified at one level with the level itself, and it comes from the observation of the real behaviour of territorial systems [6]. Generally, distribution of population among the cities is such that there are few big centres, and a lot of smaller urban cores.

Even though SLEUTH model has been efficiently used in simulation of urban dynamics, it's possible to apply it also to evolution of territorial systems on large scale. The principles which rule the urban development (described by SLEUTH parameters) can be seen also in a higher observation level: for example, generation of a new urbanized cell, due to dispersion or spread, could represent one or more buildings of the same city, or a new urban centre which will grow thanks to the effect of breed coefficient; in the same way, the systems of cities take into account, for their growth, slope and road network proximity. The decision to consider the power law in order to simulate those territories can be well understood when we consider one of its main proprieties, that scale invariance, and as for urban development mechanisms, discussed previously, its validity is independent from the considered scale.

Simulation of a territory to verify Zip's rule (rank-size) refers to a spatial pattern produced by an iterative process with a mechanism of allometric (differentiated) growth: we followed this logic for building the model input layers. Observing simulation output (calibration set is DI=0, BR=1, SP=0, SR=7 and RG=60), it's possible to notice how it respects territorial organization described by the law: we observe to the growth of a lot of very little centres equal-spaced from each others, and gravitating, in an ordered way, around big dimension "cores" situated in accessible places reached by the road network (radial transportation network, according to Wu's road model [7]).

We have also the possibility to verify how this experiment fits the law using a numerical analysis. As size we can use the extension of the cities, and not population anymore (but they are proportional, so we can exchange one with the other). Through a graphical and numerical analysis of the map we can extract the empirical data for rank-size rule.

We can observe 67 clusters on our ideal territory, and the rank will go from 0 for the largest mass, to 66 for the smallest mass (We can recognise just 4 different class of size of cities – masses - , but we will have much more differences in size, considering other iterations in the process of territory building). Plotting rank and size together in a bi-logarithmic graph we have a definitive confirmation about how the functioning of SLEUTH can recognise and interpret a rank-size structure in a good way: the number of centres grows in a power way with rank (using logarithms this relationship becomes linear, and an example of scale invariance).

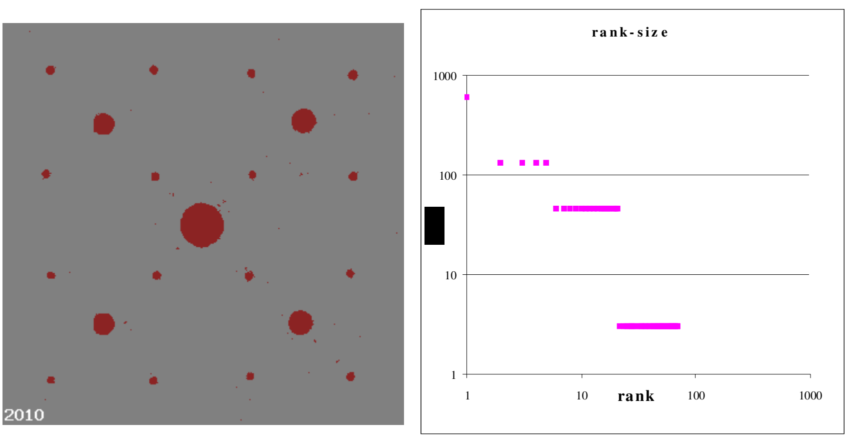

Fig. 1. Left: output image of the last year of prediction: it's possible to distinguish different level of urban centres dimensions (simulation date range: 1990-2010). Right: rank- size rule on the data of the ideal case study in logarithmic coordinates.

Having verified the ability of the model to represent and reproduce a hierarchically organized territory, it's also interesting to see how parameters combination can reproduce a hypothetic urban sprawl.

In this analysis, input layers were realized "ad hoc" for this type of simulation; and some hypothesis are necessary [8]: morphologically homogeneous territory (to guarantee an equal development probability for each cell at the beginning); no urban restrictions and constraints; "star shaped" urbanized area, which generally derives from the radial distribution of the road of transportation network. Calibration for this input gives values of DI, BR, SP, SR and RG parameters equal to 2, 6, 26, 1 and 1 respectively. The main parameters which can give an idea of urban sprawl phenomenon are BR, DI and SP; but even the road disposition and the resultant accessibility have influence upon it. Output suggests that urban area (dis)organization, which is typical of urban sprawl, is effectively reproduced in a quite good way. In the simulation the SP parameter, in spite of its predominant effect, can't replicate by itself alone urban sprawl phenomenon: it has to be associated with non-irrelevant BR and DI values.

The diffusion phenomenon, part of the sprawl, causes the presence of a high number of clusters. They decrease in number progressively, but remain - in average - very small.

3.3 Italian and European Case Studies

Results of Italian and European real territories are proposed to make the Project Gigalopolis database more consistent: in this way the comparison between real cases parameters values is easier and it's possible to trace general characteristics of urban growth phenomenon. In order to create land-use input layer, for case studies on real territories, we have assumed as opportune to convert our classification (Corine land cover) in the American one named Anderson Level I Classification System, also to conform ourselves to the classification system used in many other application of this model, in order to make the results much more shareable.

New applications are representing very different case studies: for geographic position, territory morphology and urban story and settlements types (one city or metropolitan area, more towns and municipalities together…).

Case studies are heterogeneous overall about technical details, such as input image dimensions and precision (cell size).

Table 1. Precision and parameters values for European and Italian applications

Region/area	*cell [ha]*	*DI*	*BR*	*SP*	*SR*	*RG*
Padova-Mestre, Italy	0,85	2	9	3	1	79
Palermo, Italy	0,25	2	26	38	70	100
Helsinki, Finland	1,07	2	100	11	1	62
Bilbao, Spain	0,45	6	22	22	12	53

The case study about the corridor between Padova and Mestre (near Venice) is quite different respect the others because we are analysing not a single city, but a territorial system, with an area of 51578 ha and 18 municipalities. The simulation made on 20 years (1997- 2017) shows a constant growth rate and a consequent linear growth of the urbanized areas, especially along road network: these results are confirmed by demographic analyses, which show a growth of the number of inhabitants in those municipalities and consequently of their extension.

The prevision made for Palermo from 1997 to 2017, otherwise, can be considered as a typical example of urban expansion “for contiguity”. This effect is given by an high value of SP parameter, higher than Italian and European mean, and this behaviour is explained by two reasons: the constraint factor, that is the topological structure of the areas outside the city; and the phenomenon of the suburban growth, confirmed by a parallel analysis of commuters and residence transfers of people.

The case of Helsinki, instead, it’s an example of the saturation of urbanized areas; whereas the simulation on the future of Bilbao shows a moderate growth near the city boundaries.

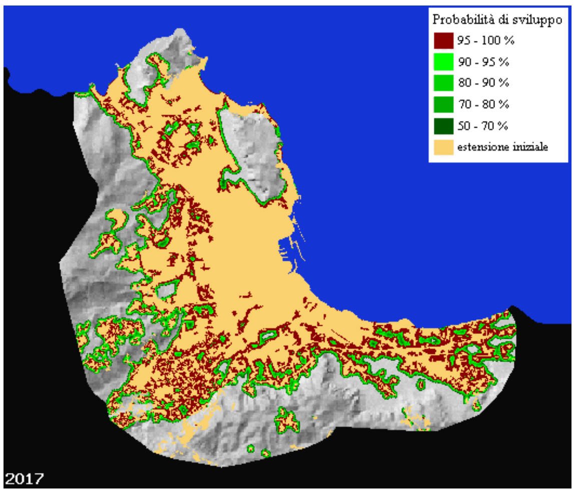

Fig. 2. Urban growth (1997-2017) and associate probabilities in Palermo, Italy

4 Remarks and Observations

The comparison with results from other cases can be performed integrating our results with Project Gigalopolis available database. So it’s possible to understand SLEUTH strength theoretical and methodological bases and to individualize, in a concise way, common characteristics of urban expansion phenomena in different areas, identifying “DNA of world and cities”, based on parameters values. The aim is to realize a regression that allows not only to describe city growth with a parametric combination, but also to deduce city or territory expansion by knowing the intrinsic effects of different parameters set. An opposite direction than calibration is ideally followed. Which actions and types of growth can a certain combination describe?

A comparison can be affected among parameters based on different geographic location case studies to understand how they can be distinguished in different territory. It's undeniable that social-economic, building and urban differences exist among different continents: they can emerge by this comparison. Instead the resistance parameter based on slope is difficult to generalize because it's typical of a land and can be traced back social-economic factors.

From it follows that: 1) a low value of DI is noticed in historical cities and metropolitan areas; in Italy and Europe there is a different space competition than in USA (max ID values); 2) BR is maximum in Europe because there is a very rational land use: when an installation occurs, its possibilities are exploited at its maximum; 3) the more the cities development is quick and recent (a growth that spreads at first from the edges), the more SP reaches high values: the maximum SP values are referred to cities which have known an economic and social boom (Mexico City, Houston, Tijuana); this is attested by the fact that minimum SP values are registered in Italian and European cities; 4) RG is often maximum in Italy and decreasing respectively in Europe, USA and other Asian and African countries. BR high and DI low values can be associated to planned and monitored territorial systems (Netherlands, Helsinki, lands which are also very flat too). There is a difference between the coastal and inland cities attitude: the firsts seem to be associated to highest DI values, the seconds refer to lower RG.

From these qualitative speculations, general principles are deduced and these can be used to describe different types of urbanization according to various parameters combination, performing the so called "parameters - real case" regression (Tab. 2). Using these methods, an effort to reproduce urban growth in Milan (between 1980 and 1997) was performed. According to the previous considerations, a set of DI=8, BR=100, SP=17, SR=1, RG=100 was chosen; results validation is possible thanks to the known situation in 1997. The obtained results are qualitatively good (right location of new settlements), but there is a trend to underestimate (-1%) the urban area, due to the presence in the Exclusion input layer of constraints representing the South Milan Agricultural Park from 1980 (but funded in 1990).

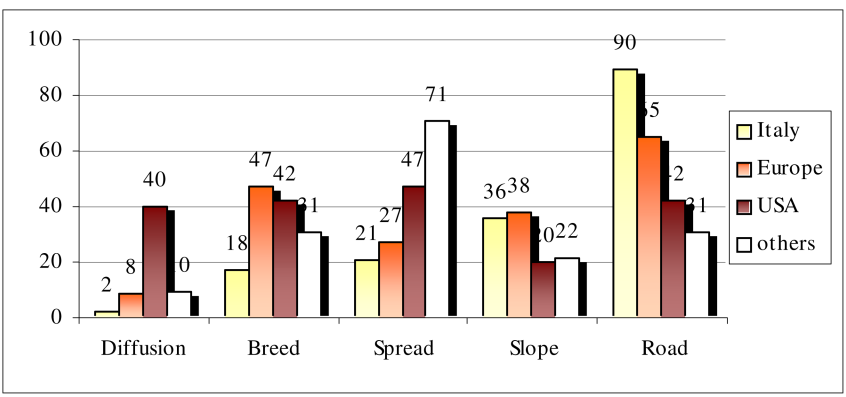

Fig. 3. Comparison between parameters values in different counties and cities in the world

Table 2. Parameters values ranges for the description of different urban development kinds

kind of urban area	hypothetical parameters values			
	DI	*BR*	*SP*	*RG*
recently developed metropolis	25-40	>50	>80	>50
urban sprawl	10-20	10-30	10-30	>50
well-established, planned city	<5	>90	<10	40-60
strongly restricted zone	<<5	100	<10	<10
metropolis with 'satellite cities'	5-10	30-40	10-30	>90

5 Conclusions

Parameters manipulating is the most synthetic approach to control urban dynamics. Being SLEUTH a trend extrapolator (using a historic database), it's possible to intuitively understand which parameter combination can describe urban dynamics for an urban complex typology (town, cities, metropolitan areas); it's possible to overcome absence of bi-univocal correspondence between parameters and growth phases using this kind of regression. Contextualizing real new case studies and methodological analysis permits to trace an inductive experimental approach, of which validity is confirmed by Milan application.

In the future, the intensive use of SLEUTH model for wide areas can be realized overcoming the computational problems, due to input images dimension and the large number of states explored by the automaton, thanks to parallel computing techniques, that is using multi-processor endowed pc or with workstations group. The whole CA cells space can be investigated dividing it in subset or subspaces and allocating these parts of study area to different computers. In this direction the intent is to integrate SLEUTH uses with the so called Computational Grid [9]. So the research continues in two directions: on one hand using the model as a tool improving performances; on the other hand investigating proprieties, using sensitivity analysis.

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