Cellular Automata-Based Spatial Dynamic Modeling for Analyzing Urban Land Use Change

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Abstract—This paper analyzes land use change in Rio Claro City and its surroundings, located in the southeastern state of São Paulo, in the period from 1988 to 1995, using air-borne digital imagery and a cellular automata model. The simulation experiment was carried out in the Dinamica EGO platform and the results revealed a constrained urban sprawl, resulting from both the densification of residential areas implemented in previous years and the economic recession that led to an internal financial crisis in Brazil during the early 1990s. The simulation outputs were validated using a multi-resolution procedure based on a fuzzy similarity index and showed a satisfactory fitness in relation to the historical reference data.

I. INTRODUCTION

The intensification of the urbanization process and the rapid growth of cities worldwide was a remarkable characteristic of the 20th century. In Brazil, urbanization has been strengthened by the modernization of agriculture in parallel with the advent of industrialization. The clustering of industries in big Brazilian cities attracted huge contingents of population proceeding from the countryside and abroad, leading to urbanization booms in most cases, what further brought about environmental and socioeconomic problems in urban areas of greater magnitude. The unplanned growth in such big cities represents an overburden on the existing infrastructure services, the occurrence of down-graded housing and slums in central areas as well as the mushrooming of informal settlements in the outskirts of these cities.

In the particular case of São Paulo State, the most industrialized one in Brazil, industrialization was not restricted to the capital city, but also took place in medium-sized cities in the state inland. Rio Claro is an example in this sense and reproduced to a reduced extent the by-side effects of unplanned growth derived from the progressive concentration of industries in the city.

In order to tackle the undesired effects of unplanned sprawl and promote a sound urban planning and management, it is of crucial importance the adoption of public policies targeted to setting guidelines aimed at achieving a sustainable socio-environmental growth. Specifically regarding planning actions, it is important the availability of update and reliable data. In this respect, remote sensing technologies are particularly able

to extract information from the urban environment in spans of time that are compatible with the observed dynamics of changes as well as to spatially characterize such changes.

The employment of remote sensing for urban analysis in association with modeling tools meant to simulate urban land use change allow to quantitatively evaluate the structure and dynamics of urban morphology, providing a better understanding of the urban realm and the drivers responsible for its spatio-temporal transformations. Dynamic models of urban land use change also enable the generation of prospective scenarios, which can anticipate the impacts caused by illegal occupations, unraveling trends of urban growth and potential future patterns of urban form.

In this regard, this work is committed to analyze land use change in Rio Claro City and its surroundings, in the period from 1988 to 1995, using air-borne digital imagery and a cellular automata model. Rio Claro has acquired a relevant agri-industrial importance in São Paulo State in recent years and was selected for analysis in face of the plenty availability of cartographic and aero photogrammetric data in different periods of time since the middle of last century. This city is located on a predominantly flat relief, with an average altitude of 613 m. The municipality of Rio Claro (Fig. 1) extends over a surface of 499 km² and shelters a population of around 186,253 inhabitants [1]. The local economy is mostly based on sugarcane processing and the industry of transformation, mainly ceramics, which has rendered Rio Claro a national production pole in this sector.

II. METHODS

A. Data Pre-Processing

First, the cadastral map of Rio Claro city was subject to editing with CAD Autodesk Map. The air-borne digital imagery acquired at a 1:40,000 scale in 1988 and at a 1:25,000 scale in 1995 were then used to update the streets and hydrographic network in the respective years.

The urban land use maps related to the initial (1988) and final (1995) time of simulation were elaborated based on visual interpretation of the digital imagery, also using Autodesk Map. For the sake of generalization, twelve classes were proposed:

Figure 1. Location of study area.

1) industrial use; 2) residential use; 3) green/leisure areas; 4) institutional use; 5) commercial use; 6) mixed use (commerce/services corridors); 7) country-side houses; 8) native vegetation; 9) grasslands; 10) reforestation; 11) sugarcane; 12) mining. The driving variables of land use change were also mapped for the initial time of simulation (1988) and comprised the following fourteen continuous maps related to distances to: 1) commerce/services corridors; 2) walled residential settlements with controlled access; 3) social housing; 4) dense clusters of elementary, junior-high, and high schools; 5) moderately dense clusters of elementary, junior-high, and high schools; 6) non-paved roads; 7) paved roads; 8) railway; 9) institutional areas; 10) double-lane road network; 11) single-lane road network; 12) health care equipments; 13) faculties and university campi; 14) green areas.

All maps of variables and land use were initially generated in vector format in Autodesk Map and were later exported to SPRING, in order to allow the association of classes to polygons and further rasterization. The land use maps were exported in TIF format and the distance grids in ASCII format to IDRISI. The initial and final land use maps underwent a reclassification of the integer values associated with the land use classes, so as to eliminate the zero value and let all classes sequentially numbered from 1 to 12. The distance grids and the two land use maps were then converted to ERMMapper format, which is compatible with the Dinamica EGO platform.

B. Parameterizing the Urban Land Use Change Model in the Dinamica EGO Platform

Parameterization basically represents the set of methods or routines meant to assign weights to the input variables [2]. This stage included the procedures to generate the global and annual transition matrices, the discretization of the continuous grids of variables and the reckoning of the weights of evidence for each range of all variables.

The global transition matrix, also called single-step transition matrix, informs the total amount of change during the whole simulation period, i.e. from the initial time until the final time. In the case of simulating past events, the global transition matrix is obtained from a cross-tabulation. This matrix can be subject to some algebraic manipulations, which produce as result an annual transition matrix (or multiple-steps matrix),

according to [3]. The annual transition matrix is the result of a product among the eigen-vector of the global matrix, the eigen-value of the global matrix raised to the power $1/n$ (where n is the number of annual steps) and the inverse eigen-vector matrix.

For the reckoning of ranges in the discretization process of continuous variables, the Dinamica EGO uses a method of lines generalization proposed by [4]. The variables weights, in their turn, are calculated using the weights of evidence method, which is based on the Bayes's theorem of conditional probability and lies on the assumption of pair-wise spatial independence between variables.

C. Calibrating the Urban Land Use Change Model in the Dinamica EGO Platform

In the calibration of the model, the checking for spatial dependence or association between all possible pairs of driving variables was executed using the Cramer's Index (V) and the Joint Information Uncertainty (JIU) index, according to [5]. Values of V or JIU above 0.50 indicate a considerable spatial association between the concerned variables, and hence, one of them has to be eliminated from the model. Usually, the variable to be discarded is the one less associated with the event (land use transition). There is also an alternative possibility for such cases, which is the combination of these two associated variables in a single layer, so as to avoid redundancy of information in the model.

The next step regarded the definition of the percentages of the two transition functions of the model: expander and patcher, besides setting the internal parameters responsible for the landscape morphology. The expander function accomplishes transitions from a class i to a class j only in the vicinities of j , i.e. through expansion. The patcher function, on its turn, executes transitions from a class i to a class j only in the vicinities of classes other than j , by means of diffusion.

In the morphological characterization of landscape, the size of new patches generated by the expander and patcher functions are defined according to a log-normal probability distribution, which regulates the average size and variance of patches for each type of transition [6]. In this stage, it is still necessary to set the value for the so-called 'patch isometry index (PII)'. This index represents a numerical value ranging from 0 to 2, which is multiplied by the probability values of the eight cells belonging to the Moore neighbourhood, before the application of the transition function. A high isometry index results in compact patches, while low values are reflected in more fragmented landscape patterns [7]. In this modeling experiment, an isometry index of 1.5 was adopted, what represents a balance between compactness and fragmentation.

The calculation of the average size and variance of patches is made with the aid of the cross-tabulation map, generated in IDRISI. This map was exported to the open source TERRAVIEW GIS environment, where the polygons areas corresponding to each type of transition were extracted. Finally, through a spatial query, the average size and variance were assessed in hectares, which is the standard unit of area accepted by the Dinamica EGO platform.

D. Simulation of the Urban Land Use Change Model in the Dinamica EGO Platform

For running the simulations of land use change in Rio Claro and surroundings, the initial land use map (1988), the set of static variables containing the fourteen grids of distances (which are kept constant throughout the model run), the annual (single-step) transition matrix, and the set of weights of evidence were used. The model also incorporated the so-called dynamic variables, represented by the distance to the land use classes, which suffer changes throughout the successive time steps, which are then continuously updated at each iteration.

As a result, seven yearly simulation outputs were produced (from 1989 to 1995), together with seven maps of probabilities for each type of transition, indicating the cells mostly prone to undergo changes in land use (i.e., those owning the highest values of transition probabilities) every year. In case the generated simulation did not result close to the observed reality at the final time of simulation (1995), iterative refinement of the internal model parameters were conducted and new runs were accomplished until a satisfactory result was obtained.

E. Validation of the Urban Land Use Change Model in the Dinamica EGO Platform

The output of spatial dynamic models must be subject to a spatial fit evaluation in a neighborhood context, since simulated maps cannot be compared to reference maps on a pixel basis, but should be rather analyzed in terms of correspondence of spatial patterns within a vicinity of pixels. The validation procedure implemented in the Dinamica EGO platform is based on a fuzzy similarity index proposed by [8], which takes into account the location and the category of the analyzed cell. Hagen's method [8] considers the concept of fuzziness of location, in which the representation of a cell is influenced by the cell itself and, to a lesser extent, by the cells in its neighborhood.

The spatial validation of the best simulated map in 1995 was executed using an adaptation of Hagen's method elaborated by the Center for Remote Sensing of the Federal University of Minas Gerais (CSR-UFGM), which takes into account two maps of difference resulting from i) the subtraction between the real final and initial land use maps, and ii) the subtraction between the final simulated land use map and the real initial land use map. After the accomplishment of the validation, and considering the obtained the fuzzy similarity indices, it is possible to define whether the model is good enough for generating prospective scenarios.

III. RESULTS AND DISCUSSION

The global transition matrix for the simulation period from 1988 to 1995 is presented in Table 1. The most meaningful changes concern the transition from industrial to commercial use, from grasslands to green areas, and from residential to mixed use. Fig. 2a and 2b present the real initial (1988) and final (1995) land use maps, indicating the observed land use changes in this period, and Fig. 3a and 3b present the real final land use map side-by-side to the simulated final land use map.

TABLE 1. GLOBAL PROBABILITY MATRIX OF LAND USE CHANGE IN RIO CLARO AND SURROUNDINGS FROM 1988 TO 1995.

Land Use Transition	Transition Probability (%)
Residential to Industrial	1.39
Residential to Institutional	0.64
Residential to Mixed Use	3.83
Industrial to Commercial	5.92
Grasslands to Industrial	1.75
Grasslands to Residential	2.51
Grasslands to Green Areas	4.90
Grasslands to Country-Side Houses	0.22
Sugarcane to Industrial	0.32
Sugarcane to Green Areas	1.21
Sugarcane to Mining	0.42

Figure 2. a) Initial land use map of Rio Claro and surroundings (1988); b) final land use map of Rio Claro and surroundings (1995).

The transition from industrial to commercial use concerns the conversion of a former huge industrial plant into a mall. The second most prominent transition (grasslands to green areas) refers to local initiatives for urban greening, especially along a new ring road in the southern sector of the city; and the third most meaningful transition – from residential to mixed use – regards the expansion of commerce/services corridors along some main streets close downtown, in replacement of former residential areas. This expansion process was favored by the proximity to the already established commercial center, the closeness to residential areas, which are in fact the potential consumer market of these mixed use areas, as well as the ease of access provided by such streets.

In the specific case of the transition to residential use, one can notice the constrained growth of new areas, accounting for 2.51% in terms of conventional residential settlements and only 0.22% representing the walled neighborhoods. This limited expansion of residential areas, and consequently of urban

sprawl, resulted from both the densification of residential areas implemented in previous years with the progressive occupation of brown-fields, and the economic recession that led to an internal financial crisis in Brazil during the early 1990s [9]. The conversion to the industrial use occurred through the installation of new plants in former residential areas or in the city outskirts, mostly over grasslands and to a reduced extent replacing sugarcane crops. Some of the bordering sugarcane crops yielded place to the expansion of the roads network, while others were converted into clay extraction areas for the ceramic industries located in the Rio Claro and in neighboring cities.

Figure 3. a) Real final land use map of Rio Claro and surroundings (1995); b) simulated final land use map of Rio Claro and surroundings (1995).

The validation results for the best simulation output are presented in Table 2.

TABLE 2. FUZZY SIMILARITY INDICES FOR THE BEST SIMULATION OUTPUT FOR RIO CLARO CITY AND SURROUNDINGS FROM 1988 TO 1995.

Exponential Decay Function			Constant Function	
Window Size	Minimum	Maximum	Minimum	Maximum
3 x 3	0.44	0.51	0.45	0.57
5 x 5	0.46	0.55	0.51	0.64
7 x 7	0.48	0.56	0.56	0.68
9 x 9	0.48	0.56	0.60	0.71

IV. CONCLUSIONS AND FINAL REMARKS

Considering the purpose of this work, the adopted methodological procedures and the obtained results, and also taking into account the observed land use change in the selected period of analysis, the following conclusions and final remarks can be drawn:

- In the analyzed simulation period from 1988 to 1995, there was a limited expansion of residential areas, and consequently of urban sprawl, resulted from both the densification of residential areas implemented in previous years with the progressive occupation of

brown-fields, and the economic recession that led to an internal financial crisis in Brazil in the early 1990s.

- The generated simulation maps showed to be consistent and with a satisfactory fitness in relation to the historical reference data (real land use map in 1995). It is worth mentioning the crucial importance of a proper variables selection for the model goodness of fit.
- The employed set of remote sensing and GIS data and tools have enabled the creation of a consistent geo-relational database.
- The adoption of environmental dynamic modeling for urban studies allows the selection of interesting information for the analysis of structural elements, processes and systems encountered in a given urban landscape, even though it offers a simplified representation of the real world relations.
- Land use change modeling can subsidize local authorities in the planning and reorganization of the urban environment by means of diagnostic and prognostic analyses.

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