Modelling Urban Land Use Dynamics through Bayesian Probabilistic Methods in a Cellular Automaton Environment

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Abstract – This scientific paper is committed with building up a methodological guideline for modelling urban land use change through the "weights of evidence" statistical method and upon basis of the information related to the technical and social infrastructure of a town.

I. INTRODUCTION

Specifically regarding urban land use dynamics, it is possible to identify basically three main trends of cellular automata (CA) models in respect to their balance between stochasticity and determinism. A first one concerns the predominantly deterministic models, whose most evident representative is the urban growth study for the San Francisco Bay area, conducted by Clarke et al. (1997). A second trend relates to the stochastic models with both deterministic estimations of area for land use transition and deterministic transition algorithms. A good example of this category of models is the SIMLUCIA, conceived by White et al. (1998), in which stochasticity is present in the calculation of the probabilities of land use transition for each cell.

A third trend concerns the stochastic CA models with both stochastic estimations of area for land use transition and stochastic transition algorithms. The modelling experiment presented in this paper integrates this third category, in which the transition rules are randomised, the cell transition probabilities are calculated through Bayesian probabilistic methods ("weights of evidence"), and the Markov chain is in principle utilised for the definition of the transition rates for each possible type of land use change.

II. METHODS

A. Exploratory Analysis and Selection of Variables

Since the "weights of evidence" statistical method (to be employed in the calculation of the cells transition probabilities) is based on the "Bayes theorem of conditional probability", the selection of variables (technical and social infrastructure maps) for the modelling analysis should take into account the checking of independence amongst pairs of variables chosen to explain the same category of land use change. For this end, two methods were used: the Cramers Coefficient (*V*) and the Joint Information Uncertainty (*U*). For further details of these two indexes, see Bonham-Carter (1994). In both cases, it is necessary to obtain values from an area cross-tabulation between pairs of maps of variables under analysis. For the Cramers Coefficient, the empirically established threshold was *0.45*, and for the Joint Information Uncertainty, *0.35*. As none of the association measure values surpassed the thresholds, no variables preliminarily selected for modelling have been discarded from the analysis.

B. Estimation of Transition Rates

In order to calculate land use transition rates for Bauru in the period 1979-1988, a cross-tabulation operation was made between the initial and final land use maps so as to generate transition percentages for the five existent types of land use change. For the estimation of land use percentages in the case of modelling land use change forecasts through DINAMICA, the Markov chain (See JRC and ESA, 1994) is to be employed.

C. Reckoning of the Cells Transition Probabilities

As previously said, the "weights of evidence" statistical method, employed in the calculation of the cells transition probabilities, is based on the "Bayes theorem of conditional probability". Basically, this theorem concerns the favourability to detect a certain event, which can be in the current case a given category of land use change (e.g. non-urban use to residential use, *R*), provided that an evidence (e.g. water supply area, *S*), also called explaining variable, has already happened. The equations of the Bayes theorem can be expressed in an *odds* form. *Odds* are defined as a ratio of the probability that an event will occur to the probability that it will not occur. The weights of evidence method uses the natural logarithm of *odds*, known as *log odds* or *logits*. In this way, $P\{S \mid R\} / P\{S \mid \overline{R}\}$ is known as the *sufficiency ratio* (*LS*), and $\log_e LS$ is the *positive weight of evidence* W^+, which is calculated from the data (Bonham-Carter, 1994). For the particular case of the DINAMICA simulation model, adopted for the modelling experiment being considered, the cells transition probabilities are calculated through a formula that converts *logit* into conventional conditional probability, as follows:

$$P_{x,y}(R / S_1 \ldots S_n) = \frac{O(R) \cdot e^{\sum_{i=1}^{n} W^{+}_{x,y}}}{1 + O(R) \cdot e^{\sum_{i=1}^{n} W^{+}_{x,y}}} \qquad (1)$$

Using the values for the positive weights of evidence (W^+) and maps of transition produced by means of reclassification procedures upon the 1979-1988 cross-tabulation map, the DINAMICA simulation model will calculate the cells transition probabilities and then generate the respective transition probabilities maps for each of the five types of land use change existing in Bauru in the considered time span. Some of these transition and probabilities maps are seen next (Fig. 1 to 6).

D. Model Calibration

Empirical procedures were adopted for the calibration of the model, such as visual comparative analysis, for each type of land use change, amongst the preliminary simulation results, the transition probabilities map and the land use transition map. The final decision towards the inclusion or exclusion of a given evidence will always rely upon a broad judgement, in which the environmental importance of the evidence and its coherence concerning the phenomenon (land use transition) being modelled are analysed.

The probability of certain non-urban areas in the city of Bauru to shelter residential settlements largely depends on the previous existence of this type of settlements in their surroundings, on the greater proximity of these areas to commercial activities clusters as well as on the available accessibility to such areas.

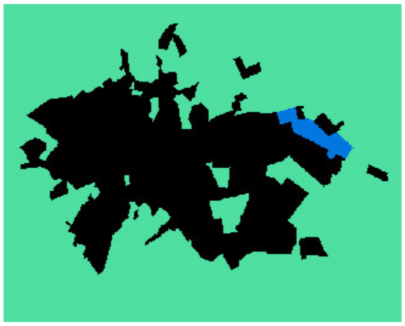

Fig. 1 - Map of land use transition "non -urban – industrial" for Bauru, 1979-1988.

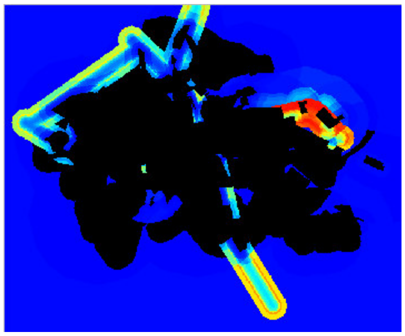

Fig. 2 - Map of transition probabilities "non -urban – industrial" for Bauru, 1979-1988.

Fig. 3 - Map of land use transition "residential – services" for Bauru, 1979-1988.

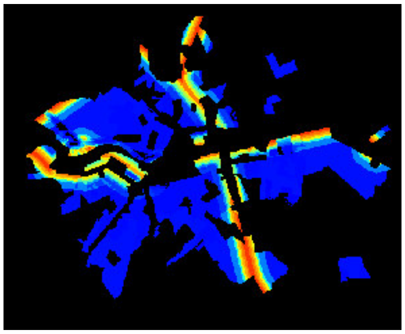

Fig. 4 - Map of transition probabilities "residential – services" for Bauru, 1979-1988.

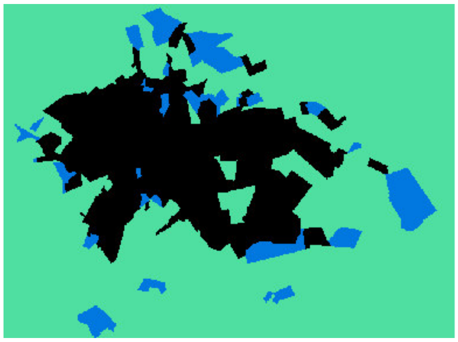

Fig. 5 - Map of land use transition "non -urban - residential" for Bauru, 1979-1988.

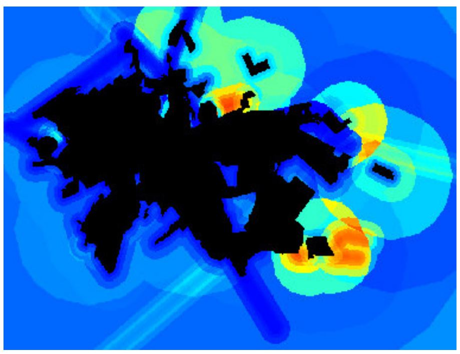

Fig. 6 – Map of transition probabilities "non -urban – residential" for Bauru, 1979-1988.

As to the transition of non-urban areas to industrial use, there are two great driving forces: the nearness of such areas to the previously existent industrial use and the availability of road access. This can be explained by the fact that in the industrial production process, the output of certain industries represent the input of other ones, what raises the need of rationalisation and optimisation of costs by the clustering of plants interrelated in the same productive chain. Furthermore, plots in the vicinities of industrial areas are often prone to be devaluated for other uses, what makes them rather competitive for the industrial use.

Regarding the transition of non-urban areas to services use, three factors are crucial: the proximity of these areas to clusters of commercial activities, their closeness to areas of residential use, and last but not least, their strategic location in relation to the N-S / E-W services axes of Bauru. The first factor accounts for the suppliers market (and in some cases also consumers market) of services; the second factor represents the consumers market itself; and the third factor corresponds to the accessibility for both markets related to the services use.

The transition "residential to services use" supposes the insertion of services into previously consolidated urban areas. In this way, since this transition type already takes place amid the suppliers and consumers markets, it will solely prioritise the strategic location in relation to the N-S / E-W services axes of Bauru, besides of course, the existence of water supply, which in the specific case of Bauru does not correspond to the whole urbanised area.

Finally, the last type of land use transition concerns the shift from residential use to mixed use. The mixed use zones, which actually play the role of urban subcentres, constitute a sort of commercial centres consolidation, which at a later stage also start to attract services and social infrastructure equipments besides commercial activities themselves. Therefore, new mixed use zones arise in more peripheral areas, where a greater occupational gathering is at the same time assured. Thus, the decisive factors for this last type of land use change are:

- existence of medium-high density of occupation (higher density values only occur in the central commercial zone of the town or in the immediacies of already existent mixed use zones);
- presence or proximity of social housing settlements (for they shelter the greatest occupational densities in more peripheral areas, and hence, feasible consumers markets);
- nearness to planned or peripheral roads, since new mixed use zones arise in farther areas of the town.

III. RESULTS AND DISCUSSION

As it can be observed in Fig. 7 through 10, the services corridors were well modelled in all simulations, specially in S2 and S3. The industrial use as well as the mixed use zone, situated in the northwest, were well detected in all of the three simulations. The shifts from non-urban areas to residential use represented the most challenging category of transition in the modelling experiment at issue. This lies on the fact that the detached residential settlements contours are associated with the real state properties limits. Since legal actions for the merging or split of plots may occur at any time and drastically alter their form, such boundaries can be regarded as highly unstable factors.

To conclude, it is worth stressing here the wide feasibility (and the cells transition probability maps are a concrete prove) to optimise the simulations results by means of a model which embraces more refined algorithmic logics (fractal parameters, semi-stochastic rules, etc.), suitable for the urban phenomena modelling under consideration.

IV. STATISTICAL VALIDATION OF THE MODEL

Constanza (1989) presents a multiple resolution method entitled "*Goodness of Fit*", in which a sampling window, that can adopt different sizes, moves over the entire images considered, and the average fit between two given scenes (the real and the simulated one) for a particular window size is calculated. This method was applied for the simulation results of Figures 8 to 10, with sampling window sizes of 3x3, 5X5 and 10x10. The values of FIT were 0.902937 for S1, 0.896092 for S2 and 0.901134 for S3.

V. CONCLUSION

The urban land use dynamics models have proved to be useful for the identification of main urban growth vectors, what enables local planning authorities to manage and reorganise (if it comes into question) city growth. The urban expansion forecasts as well help decision makers from the private sphere in defining priorities as to where and how intense to invest. Also the organised civil society can profit from the modelling forecasts in order to enhance, by legal means, demanding social movements for the implementation of social and technical infrastructure, since their requests and respective arguments shall be based on realistic short- and medium-term urban growth trends. Finally, it is worth reminding that the "weights of evidence" statistical method is not constrained by the straitjacket of rigid theories devices. Since this a wholly empirical approach, its applicability can be extended to further Brazilian and worldwide cities, provided that the minimum necessary sets of evidences maps are available.

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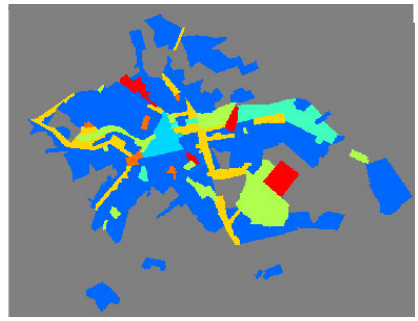

Fig. 7 – Final land use map of Bauru - 1988.

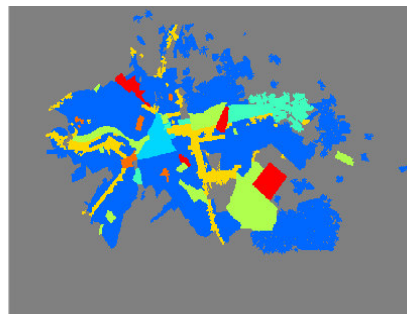

Fig. 8 – Land use simulation 1 (S1) for Bauru, 1979-1988.

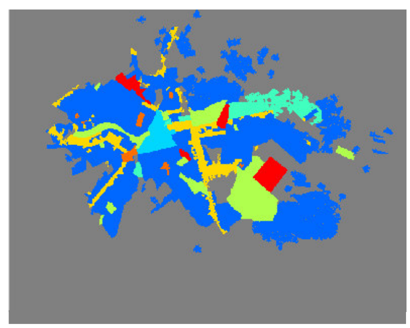

Fig. 9 – Land use simulation 2 (S2) for Bauru, 1979-1988.

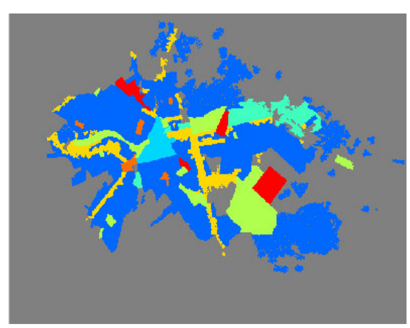

Fig. 10 – Land use simulation 3 (S3) for Bauru, 1979-1988.