
Calibration of a cellular automata model to simulate land-use changes in the Calgary region

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Abstract

This paper describes a semi-automated interactive method that has been implemented to calibrate a cellular automata (CA) model developed to simulate land-use changes in the Elbow river watershed in the Calgary region, Alberta. This procedure involves the use of a spatio-temporal GIS database that integrates land-use maps, and physiographic and socio-demographic data collected in the study area over the last 25 years. First, five historical land-use maps that have been produced from Thematic Mapper images are read, and factors responsible for driving the land-use changes (slope, land value, distance to the road network, etc.) are identified. Then, a frequency histogram is produced for each combination of land-use changes, neighborhood configuration, and driving factor. All this information is analyzed to determine the transition rules that can be applied for the simulation. This calibration procedure offers several advantages. It is highly flexible and interactive and allows a user to dynamically display the influence of each driving factor on past land-use changes and to select how this factor will be taken into consideration in the CA model to forecast future land-use development. In addition, multiple processes driving a land-use change can be identified and independently simulated. This project is conducted in collaboration with the Calgary Regional Partnership and a selected group of planners and land managers who will use this simulation model as a decision support tool to investigate the impact of various management scenarios on future land development.

Introduction

Cellular automata (CA) are simulation models that are increasingly used to study a large number of spatio-temporal phenomena including fire growth, rangeland degradation, land-use/cover change and urban development (Clarke et al., 1997; Jenerette and Wu, 2001; Cheng and Masser, 2004; Favier et al., 2004; He et al., 2004; Ménard and Marceau, 2007; Hernandez Encinas et al., 2007). In such a model, space is represented as a matrix made of a regular arrangement of cells having the same dimension and shape. Each cell has a state value and evolves in time through simulation characterized by discrete time steps. Transition rules, applied at each time step, dictate how the different cell states will react to state configurations present in their neighborhood. The
neighborhood can be local or extended to take into account regions of influence of different sizes. In some CA, a set of constraints can be imposed that specify the number of cells allowed to change state at each time step of the simulation. Previous studies have demonstrated that CA models are remarkably effective at generating realistic simulations of land-use patterns. Their potential has been recognized in impact assessment, land-use planning, and social policy, and several CA models have been designed as prototypes of spatial decision-support systems for urban and regional planning.

A main challenge when implementing a CA model is the calibration procedure. Calibration is the process by which numerical values are assigned to the model parameters to ensure that the model accurately reproduces the real patterns (Silva and Clarke, 2002). There is no standard way to calibrate a CA model and different approaches have been applied. The first type is based on trial and error; the best set of parameter values is determined from available data sets using visual comparison. The other type relies on statistical methods, such as Monte Carlo (Jantz et al., 2003) and logistic regression (Wu, 2002; Fang et al., 2005). These approaches suffer several limitations including: difficulty to interpret the parameters and their values, parameter values are hard-coded in the model, computationally intensive, and difficulty to replicate. The objective of this paper is to describe a novel semi-automated and interactive approach that has been developed in attempts to overcome these limitations.

The procedure involves the use of a spatio-temporal GIS database that integrates land-use maps, and physiographic and socio-demographic data collected in the study area over the last 25 years. Calibration is performed for every desired type of land-use change. Similarly to most land-use CA, the transition rules are expressed as a linear combination of factors that takes into account the neighborhood configuration and the cell characteristics specified by the user, such as the distance to a main road. The neighborhood of a cell is defined as a set of one or more concentric rings, covering at least the extent of the Moore neighborhood (eight adjacent cells). First, historical land-use maps that have been produced from remote sensing Thematic Mapper images are read, and factors responsible for driving the land-use changes (slope, land value, distance to the road network, etc.) are identified. The model looks at all the cells that have experienced a given land-use change and their neighborhood configurations in all the historical data. For each type of change (for each combination of initial and final land-uses), for each land-use in each neighborhood ring and for each cell characteristic, a frequency histogram representing the distribution of the neighborhood configuration and cell characteristics of all the cells that have experienced this change in the past is displayed (Figure 1). These histograms are then used to identify the parameters as well as the ranges of values of these parameters that correspond to significant land-use changes in the watershed. Multiple ranges identified on a histogram means that different dynamics driving the land-use change are co-occurring. The mean value and the standard deviation are recorded for every identified range and their combination becomes the transition rules. During the simulation, the neighborhood configuration of each cell is compared against the transitions rules. The transition rule that has the best Resemblance Index (RI) as defined in Equation 1 is the one that will make the cell change its state.

\[ RI = \sum_{i=1}^{n} \frac{(n_i - x_i)}{\sigma_i} \]  
(Eq. 1)
where $m$ is the product of the number of neighborhood rings and the number of land-use types, $n_i$ is the number of cells of the corresponding land-use in the corresponding neighborhood ring around the cell to be updated, $x_i$ is the matching transition rule mean and $\sigma_i$ is the matching transition rule standard deviation.

![Figure 1](image)

**Figure 1**: Distances to a main road for the cells that have changed from forest to agriculture in the Elbow river watershed between 1985 and 2001. The graph indicates that 90% of the cells were located within 2 km of a main road.

The CA model can be used to forecast land-use changes when the same trends that have been observed in the past are maintained or to drive the changes in a direction specified by the user. Five types of constraints have been implemented in this version of the model to specify the amount of cells that must change, or not, their land-use attribute. They can be applied at any simulated date and include:

1. no development zone: the user specifies one or more zone in which one or more type of change can not occur;
2. global objective of development: the user specifies, for the whole study area, the number of cells that must follow one or more types of change;
3. local objective of development: the user specifies in one or more zone the number of cells that must follow one or more type of change;
4. global development help/restriction: the user specifies, for the whole study area, a positive or a negative increment factor that will be multiplied by the RI of each cell of one or more type of change. Chances of having the specified type of land-
use changes increase or decrease as the rank of the RI corresponding to different land-use changes is modified.

5. local development help/restriction: the user specifies in one or more zone a positive or a negative increment factor that will be multiplied by the RI of each cell of one or more type of change.

**Results**

This CA has first been tested using the Conways’ Game of Life and then applied to simulate land-use changes in the Elbow river watershed in Alberta. In the first case, images resulting from the simulation have been employed as input data to the CA model; the model correctly reproduced the dynamics of the system, using another initial condition map. The CA model has also been able to reproduce the land-use dynamics in the Elbow River watershed, using a cell size of 30 * 30 m and six land uses. The model has been calibrated with historical land-use maps for the years 1985, 1992, 1996 and 2001 and has been run from 1985 to 2006. The simulation outcomes have then been compared with an independent land-use map. Results reveal that the correct number of cells that must change to each specific land use is correctly computed and allocated by the CA model, except for the forest land-use that shows a low level of accuracy. The model can find the adequate land-use change to be applied even if the same neighborhood configuration could lead to different land-use change. A sensitivity analysis will be conducted to identify the best neighborhood rings, cell size as well as the best ranges of values in the calibration process.

**Conclusion**

This CA model has been designed to capture multiple dynamics driving the land-use changes, which represents a major improvement over the conventional approach. The transition rules are easy to obtain and meaningful whereas in most CA models, transition rules have only one of the aforementioned properties. The user can use his expertise to create these rules and increase his knowledge about the factors that drive the landscape dynamics during the process. Since there are no embedded transition rules nor predefined types of urban growth, the model is universal and reproducible. Finally, the calibration and execution times are much faster than they are in most CA models, due to an innovative way of handling and processing the data.
References


Biography

Jean-Gabriel Hasbani is a M.Sc. student in the Department of Geomatics Engineering at the University of Calgary, Alberta, Canada. He has obtained a bachelor degree in Physical Geography and a certificate in Programming at the University of Montreal. He has an expertise in spatio-temporal geovisualization, remote sensing image classification, GIS databases, model calibration, and in programming and modeling.

D. Marceau is professor at the Department of Geomatics Engineering at the University of Calgary and a member of the Institute for Sustainable Energy, Environment and Economy. Her research program is focused on designing and implementing dynamic individual-based models, namely cellular automata and multi-agent systems to investigate complex environmental resource management problems and guide decision making.