Computers, Environment and Urban Systems 62 (2017) 113–124

Contents lists available at ScienceDirect

Computers, Environment and Urban Systems

journal homepage: www.elsevier.com/locate/ceus

Stable models for metastable systems? Lessons from sensitivity analysis of a Cellular Automata urban land use model

Richard Hewitt [a,b,*], Jaime Díaz-Pacheco [c,d]

[a] Observatorio para una Cultura del Territorio, C/ Duque de Fernán Núñez 2, 1ª planta, 28012 Madrid., Spain
[b] James Hutton Institute, Craigiebuckler, Aberdeen AB15 8QH, Scotland, UK
[c] Departamento de Geografía Humana, Universidad Complutense de Madrid, C/ Profesor Aranguren, s/n, 28040 Madrid, Spain
[d] Cátedra Reducción del Riesgo de Desastres, Ciudades Resilientes, Facultad de Humanidades, Universidad de La Laguna, Campus de Guajara, s/n, 38071 Tenerife, Spain

ARTICLE INFO

Article history:
Received 22 February 2016
Received in revised form 24 October 2016
Accepted 25 October 2016
Available online xxxx

Keywords:
Complexity
Urban systems
Cellular automata
Sensitivity analysis
Metastability
Land use model

ABSTRACT

This research suggests that the degree of variability in a Cellular Automata (CA) urban land use model application may be linked to the application's suitability for modelling complex urban systems. Although highly stable models may be perceived as desirable, because they produce reliable, realistic-looking land use simulations, there is a risk that they may not be able to simulate true urban complexity. To test this hypothesis, variability was analysed through a sensitivity analysis in which a calibrated CA land use model application was modified repeatedly to produce a range of model variants with different characteristics. Since model scale is a key attribute known from literature to strongly influence model results, sensitivity analysis was conducted with reference to the scale-related elements (cell resolution, neighbourhood effect) in the model. Variation was found to be slight even between applications having widely differing cell resolutions and neighbourhood distance decay effects. It is contended that this is not an application-specific question, but a feature of these types of models more generally, where simple rules, strong constraints and a low degree of stochastic variation tend to produce highly stable simulation outcomes. To address the question of whether such stable model applications are really suitability for simulating urban complexity, the applications are discussed with relevance to three key indicators of complexity; 1) spontaneous emergence, 2) bifurcation; and 3) critical transitions. Finally, we ask whether the requirement of metastability necessary for calibration of such models violates the assumption of freedom from systemic constraints that would allow true complexity to be simulated. Some suggestions are made as to how these issues might be resolved in future, allowing a new generation of models to emerge.

1. Introduction

Cellular Automata (CA) models of land use change are popular and useful tools for simulating complexity in urban systems (e.g. Batty & Torrens, 2001; Besussi, Cecchini, & Rinaldi, 1998; Clarke, Hoppen, & Gaydos, 1997; White & Engelen, 1993). Early model applications were able to simulate complex patterns of urban growth, self-organization and change (Clarke et al., 1997; White & Engelen, 1993). However, it has since become common practice to apply constraints to the CA model to improve realism and application to real world problems. Though this has arguably made the models much more useful, no detailed research is available about the degree to which constraints may limit the CA's ability to simulate complexity. A highly constrained CA model may jettison this capability completely and predictably return only a few basic patterns. A sensitivity analysis, therefore, is useful in a CA model, not so much to ensure that model behaviour is stable, but rather to ensure that it is not so stable as to prevent any possibility of that some of the more interesting features of complex systems (emergence, bifurcation, critical transitions) might appear.

In this paper this question is addressed by developing, calibrating, validating, and undertaking detailed sensitivity analysis on a land use model for the region of Madrid, using the well-known and widely used Cellular Automata (CA) modelling framework developed by White and co-workers (e.g. White & Engelen, 1993; White, Engelen, & Uljee, 1997; White & Engelen, 2000 etc), in its most widely known software implementation, Metronamica.

2. Research background

2.1. Modelling complexity in urban systems

The theory of cities as complex systems has been attributed to Peter Allen (e.g. Allen & Sanglier, 1981; cited by Portugali, 2013) but is rooted in earlier developments in systems theory (e.g. Churchman, 1968) and far-from-equilibrium thermodynamics (Prigogine, 1980). In a landmark paper, White and Engelen (1993) showed that a computer model based on Cellular Automata (CA) could be used to generate realistic

* Corresponding author at: Observatorio para una Cultura del Territorio, C/ Duque de Fernán Núñez 2, 1ª planta, 28012 Madrid., Spain.

http://dx.doi.org/10.1016/j.compenvurbsys.2016.10.011
0198-9715/

simulations of urban systems in which key features of complex systems identified in the earlier literature, e.g. spontaneous emergence of patterns, bifurcation, and irreversible state transitions (e.g. Allen & Sanglier, 1981; Prigogine, 1980) were clearly present. White and Engelen's model provided a template for simulation of complex patterns of urban change, and has since seen many applications around the world (e.g. Barredo, Demicheli, Lavalle, Kasanko, & McCormick, 2004; Lajoie & Hagen-Zanker, 2007; Wickramasuriya, Bregt, Van Delden, & Hagen-Zanker, 2009). Since its initial development the model has been adapted to include, in particular, a constraint on the number of cells that transform at each time step (Demand); the influence of infrastructure networks (Accessibility); biophysical factors such as terrain slope or aspect (Suitability); and planning restrictions (Zoning). Despite these additions, the CA transition rules set (Neighbourhood dynamics) and the stochastic perturbation term (v), remain at the core of the model. However, at present, it remains unclear to what extent these additional constraints can be applied before the CA is effectively overpowered and produces only predictable outcomes. In this paper, we address this question with respect to three specific characteristics of complexity identified in earlier models:

1. Bifurcation. As Prigogine and Stengers (1997) have noted, bifurcation is a key property of far-from-equilibrium systems. In such a system, fluctuations, produced for example, by dissipative processes, can lead the system to "choose" between alternate states or pathways. If bifurcation occurs repeatedly as part of a process chain, the system takes on a branching structure giving rise to a very large number of possible end states which are unpredictable *ex ante*. Bifurcations in the model described here are the result of a random process introduced through the stochastic factor (v) which affects the land use allocation decisions. Thus a land area that was not especially attractive for a particular land use may suddenly become so. Cells are allocated in the next time step to this new pole of attraction, causing a cluster. The neighbourhood effect caused by the new cluster causes this cluster to grow. Since the demand is exogenously defined true spatial bifurcations can occur, because land allocated to this new cluster cannot now be allocated anywhere else. The system has been transformed in a way that could not have been predicted. This behaviour is described by White and Engelen (1997, p. 244) in their model of the island of SimLucia. A forest area on the northeast of the island was converted to agriculture in around 20% of the simulations, a result of a random allocation in an area where potential for this transition to occur was already high.
2. Emergence. For the purposes of this article, we define emergence simply as "the capability of the model to produce isolated spatial structures beyond the influence of the cell neighbourhood". This is a characteristic of all classic urban CA models (e.g. Clarke & Gaydos, 1998; White, 1998) and is also an observable property of cities themselves. We argue that a model that does not show emergent behaviour may not be suitable for simulating urban complexity.
3. Critical transitions. In theory, a self-organising system with highly innovative emergent properties and very strong bifurcations could produce transitions at the level of the system itself, causing flips from one state to another. With respect to CA models, the special bifurcation case described above in the SimLucia model (White and Engelen, 1997) might arguably also be a case of a critical transition, since, although the forest to agriculture conversion only occurred around 20% of the time, when it did, it seemed to be because the stochastic variability had caused a critical threshold to be crossed. However, it could be argued that to differentiate critical transitions from bifurcations, a state change would need to be observed at the level of the system. In the case described it's not clear that the forest-to-agriculture conversion described actually caused a significant system transformation. Clearly, though, where emergence and bifurcations can be convincingly demonstrated, the possibility that this behaviour may eventually culminate in a critical transition should not be ruled out.

3. Aims

The aim of this work is therefore to explore how variability in the scale of the model, reflected through the cell resolution and the neighbourhood effect, influences a land use model's capacity to simulate land use change, and how this may determine the usefulness of the model for simulation of complex urban systems. As a starting point for our analysis, we make three basic assertions:

1) The basis of the CA model is spatial interaction in the cell neighbourhood (neighbourhood dynamics), and this is the principal determinant of the model's dynamic behaviour.
2) Neighbourhood dynamics, do, on their own, produce spatial patterns readily identifiable as "complex", as demonstrated by the previously mentioned work of White and colleagues. These patterns are generated by the allocation of land use to cells according to a cell's potential for that land use, The complex spatial patterning is affected by the stochastic factor but unrelated to the externally generated demand.
3) The introduction of other spatial constraints like Accessibility, Suitability and Zoning, as is typically done when calibrating a standard Metronamica application, may reduce the model's capability to simulate complexity and decrease the usefulness of model applications.

4. Methods

The area selected for the analysis is the Madrid region (Fig. 1), a Spanish Autonomous Community and province with around 6 million inhabitants. This region was chosen because of the extraordinarily dynamic land use change that the region has undergone during recent decades (until the beginning of the current economic crisis around 2008), and because a highly detailed land use database documenting this change has recently become available (Díaz-Pacheco & García-Palomares, 2014).

To carry out the sensitivity analysis, a Cellular Automata (CA) urban land use model was built and calibrated for the case study area. The land use dataset used in the model was Madrid Land Use (Díaz-Pacheco & García-Palomares, 2014), a large detail scale cartographic database of land use and land cover information for the Madrid Region, covering the time periods 2000, 2006 and 2009. The Madrid Land Use dataset comprises 12 land use classes of which 7 are urban.

The modelling framework adopted was that found in Metronamica, a popular land use modelling software, which implements the CA modelling approach of White and collaborators (White & Engelen, 1993; White et al., 1997; White & Engelen, 2000 etc). In this model, the distribution of land use in a given area is represented as a raster map in which each cell has a value which represents a land use. The value of the cells can change according to a set of transition rules computed by a simple equation in which the geographic effect of a cell over its neighbours (attraction or repulsion between land use cells) represents the main driving force of change in the system. A random parameter to incorporate a degree of stochasticity into the model is also introduced. Accessibility (e.g. distance to road networks) and suitability (e.g. degree of terrain slope) parameters are introduced to align the model with the characteristics of the study region. Finally a zoning parameter can be also added to allow the influence of policies or planning scenarios to be introduced into the simulation. New cells are allocated at each step of the model on the basis of the transition potential computation (Eq. (1)) until cell demand (determined exogenously) is exhausted or all available cell space is used up.

Land use demand Δ is calculated for each yearly timestep by Δt_2-Δt_1/ t_2-t_1, where Δt_1 is the number of cells for each land use in the land use map of the simulation start date, Δt_2 is the number of cells for each land use in the land use map of the simulation end date, t_1 is the simulation end year and t_1 is the simulation start year. For simulations of future dates where Δ is unknown, it is determined in various ways; e.g. by